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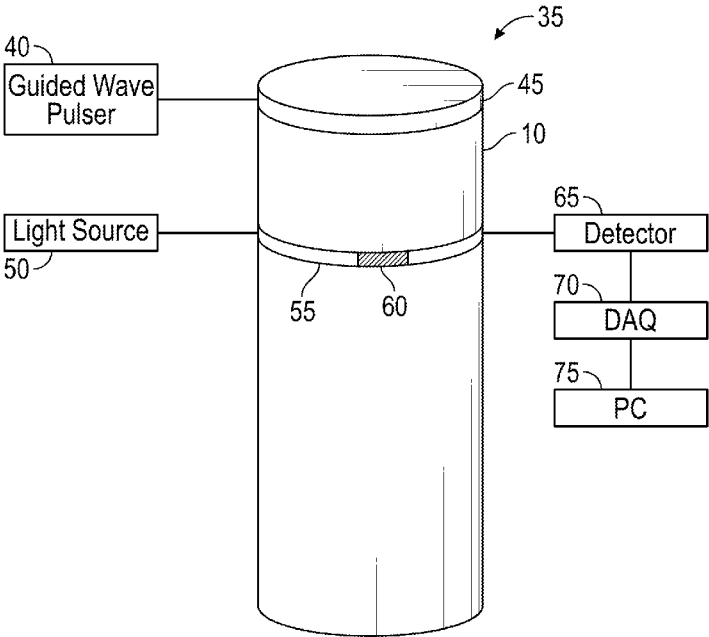


FIG. 2

(57) Abstract: A system for monitoring structural health of a nuclear fuel storage canister includes a wave assembly for exciting the canister with acoustic waves, a number of fiber optic sensor assemblies coupled to the canister exterior, a light source for interrogating the sensor assemblies, and a detector for receiving a first sensor output responsive to interrogation light while the canister is being excited with acoustic waves, and in response thereto generating active sensor data, and for receiving a second sensor output responsive to the interrogation light while the canister is not being excited with the acoustic waves, and in response thereto generating passive sensor data. A controller coupled receives the active sensor data and the passive sensor data, and analyzes either or both to detect a defect or other undesired condition of the canister or internal to the canister based on the analyzing.

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SYSTEM AND METHOD FOR MONITORING THE HEALTH OF NUCLEAR WASTE STORAGE CANISTERS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 63/492,617, filed on March 28, 2023 and titled “System and Method for Monitoring the Health of Nuclear Waste Storage Canisters,” the disclosure of which is incorporated herein by reference.

STATEMENT OF GOVERNMENT INTEREST:

[0002] This invention was made with government support under grant # DE-NE0009210 awarded by the Department of Energy (DOE). The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] The disclosed concept relates generally to the storage of nuclear waste, and, in particular, to a system and method for monitoring the health of nuclear waste storage canisters based on monitoring using fiber optic based sensors (e.g., for sensing strain, temperature or acoustic parameters) and distributed and/or quasi-distributed sensing technologies.

BACKGROUND OF THE INVENTION

[0004] In the United States and internationally, dry storage casks are increasingly used to store spent nuclear fuel rods before they are shipped to repositories for disposal. Such dry storage casks were initially designed for mid-term storage relative to the nuclear fuel cycle. In the absence of a final repository solution, however, extended use of dry storage casks is inevitable, making it necessary to assess the structural integrity of the storage casks through inspections to ensure safe and secure waste storage over the life cycle of the stored spent nuclear fuel.

[0005] Most storage casks in the United States use stainless steel canisters to confine spent fuel assemblies. After sealing, the canisters are transported to a separate spent fuel storage facility and placed in a vented (for cooling purposes) concrete overpack for protection and radiation shielding. FIG. 1 is a schematic diagram of an exemplary prior art spent fuel storage cask configuration 5 that is widely used in the industry and that is provided herein for

illustrative purposes. As seen in FIG. 1, configuration 5 includes a stainless steel cylindrical canister 10 that stores spent nuclear fuel. Canister 10 is typically fabricated by welding together two rolled and axially welded cylindrical sections of stainless steel, resulting in welded portions 15 as seen in FIG. 1. To protect and shield canister 10, it is inserted into a concrete overpack 20 with vertical guide slots 25, and sealed with a rust inhibitor. A lid 30 is provided to seal the top of configuration 5. From an inspection point of view, the shielding structure of overpack 20 allows access to the surface of canister 10 only through a narrow ventilation system.

[0006] Canister 10 serves as an important shielding barrier for the fission products that are stored therein. Therefore, the structural integrity of canister 10 is of considerable safety significance and should be absolutely guaranteed.

[0007] One potential degradation mode for canisters such as canister 10 is chloride-induced stress corrosion cracking (SCC). SCC is caused by the deliquescence of chloride-rich salts, especially given longer-than-intended storage times. In addition, welded portions 15 of canister 10 may result in high thermal residual tensile stresses that act as cracking drivers.

[0008] Another degradation mode for canisters such as canister 10 is related to the fuel rods inside of the canister body and the potential for leakages from the fuel rods. Methods have been developed to monitor helium gas leakage from vertical canisters based on a phenomenon in which the temperature at the canister bottom increases as temperature at the top of the canister decreases as helium gas leaks during storage. Operations following dry storage, such as transferring the used fuel into a transportation cask or transferring used fuel to a disposal container, may be problematic due to the potential release of radioactive fission gas into the canister fill gas. At this time there are no methods available for direct inspection of the internal components of welded storage canisters such as canister 10 once they are loaded and sealed.

[0009] The occurrence of SCC is common and recent studies using finite element analysis of residual stress fields and preliminary residual stress measurements have adequately analyzed this and are consistent with general mechanics of materials expectations. However, in-situ inspection is challenging due to the harsh environment and geometric constraints within the canister as well as the risks associated with penetrating the canister surface for external communications. The internal canister environment includes elevated temperatures and gamma radiation. According to the numerical model of a dry storage canister, the temperature and gamma radiation dose inside the canister are conservatively

177°C (350°F) and 27krad/h, respectively. In addition, the vertical axis of dry storage canisters provides severe geometric constraints.

[0010] Therefore, it advantageous to consider a suitable SHM (Structural Health Monitoring) system for inspection capable of satisfying these various challenging constraints, including the desire for external canister monitoring to eliminate canister penetration and associated risks.

[0011] Distributed Fiber Optic Sensor (DFOS) technology is an emerging technology for structural health monitoring applications. In DFOS, the entire fiber-optic cable can act as an array of sensing elements, or alternatively discrete sensor elements can be integrated along the fiber length for what is known as quasi-distributed sensing. The overall variation and spatial resolution (i.e., instrument length) of the individual sensor nodes are optimized for the specifics of the fiber optic cable. In the case of DFOS, the backscattered light may be used to characterize the strain, temperature, or acoustic disturbances in the fiber optic cable, thereby quantifying the variation in the scattered signal and generating distributed data. In the case of acoustic sensing or distributed acoustic sensing (DAS), DFOS has been used for active leak detection and to identify the risk of external threats such as landslides, construction vehicles, and others. However, the existing DFOS technology is limited in its ability to detect different potential dangers of local corrosion or pipeline structural integrity prior to the occurrence of a breach or failure due to the relatively weak acoustic response under natural operational conditions and the presence of various background contributions. In addition, fully DFOS is limited by the attainable range and spatial resolution, dependent upon the range of acoustic frequencies desired to monitor. A need exists to adapt and optimize the application and practice of FOS and DFOS for nuclear canister monitoring.

SUMMARY OF THE INVENTION

[0012] In one embodiment, a system for monitoring the structural health of a storage canister for storing spent nuclear fuel is provided. The system includes a wave assembly structured and configured for exciting the canister with acoustic waves, a number of sensor assemblies coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices, a light source structured and configured for providing interrogation light to the number of sensor assemblies, and a detector coupled to the number of sensor assemblies, the detector being structured and configured for receiving a first output of the number of sensor assemblies responsive to the interrogation light in an active mode of operation while the canister is being excited with

acoustic waves, and in response thereto generating active sensor data, and the detector also being structured and configured for receiving a second output of the number of sensor assemblies responsive to the interrogation light in a passive mode of operation while the canister is not being excited with the acoustic waves, and in response thereto generating passive sensor data. The system also includes a controller coupled to the detector that is structured and configured for receiving the active sensor data and the passive sensor data, and for analyzing either or both of the active sensor data and the passive sensor data and detecting a defect in the canister based on the analyzing.

[0013] In another embodiment, a method of monitoring the structural health of a storage canister for storing spent nuclear fuel is provided that includes selectively exciting the canister with acoustic waves, wherein a number of sensor assemblies are coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices, receiving a first output of the number of sensor assemblies responsive to interrogation light in an active mode of operation while the canister is being excited with the acoustic waves, and in response thereto generating active sensor data, and receiving a second output of the number of sensor assemblies responsive to interrogation light in a passive mode of operation while the canister is not being excited with the acoustic waves, and in response thereto generating passive sensor data, and analyzing in a controller either or both of the active sensor data and the passive sensor data and detecting a defect in the canister based on the analyzing.

[0014] In yet another embodiment, a method of monitoring the structural health of a storage canister for storing spent nuclear fuel is provided that includes exciting the canister with acoustic waves, wherein a number of sensor assemblies are coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices, providing interrogation light to the number of sensor assemblies in an active mode of operation while the canister is being excited with the acoustic waves, receiving a first output of the number of sensor assemblies responsive to the interrogation light and in response thereto generating active sensor data, and analyzing in a controller the active sensor data and detecting a defect in the canister based on the analyzing.

[0015] In still another embodiment, a method of monitoring the structural health of a storage canister for storing spent nuclear fuel is provided, wherein a number of sensor assemblies are coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices. The method includes providing interrogation light to the number of sensor assemblies in a passive mode of operation while

the canister is not being excited with acoustic waves; receiving a first output of the number of sensor assemblies responsive to the interrogation light, and in response thereto generating passive sensor data, and
analyzing in a controller the passive sensor data and detecting a defect in the canister based on the analyzing.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] A full understanding of the invention can be gained from the following description of the preferred embodiments when read in conjunction with the accompanying drawings in which:

[0017] FIG. 1 is a schematic diagram of an exemplary prior art spent fuel storage cask configuration that is widely used in the industry and that is provided herein for illustrative purposes;

[0018] FIG. 2 is a schematic diagram of a structural health monitoring (SHM) system for inspection of nuclear waste storage canisters according to one non-limiting exemplary embodiment of the disclosed concept;

[0019] FIG. 3A and FIG. 3B show an exemplary excitation signal, in the time domain and frequency domain, respectively that may be employed in connection with the disclosed concept;

[0020] FIG. 4 is a schematic diagram of an SHM system for inspection of nuclear waste storage canisters according to an alternative non-limiting exemplary embodiment of the disclosed concept;

[0021] FIG. 5 is a schematic diagram of an SHM system for inspection of nuclear waste storage canisters according to another alternative non-limiting exemplary embodiment of the disclosed concept;

[0022] FIG. 6 is a schematic diagram of an SHM system for inspection of nuclear waste storage canisters according to another alternative non-limiting exemplary embodiment of the disclosed concept;

[0023] FIG. 7 is a schematic diagram of a feature extraction based technique, which shows feature extraction from a time domain and a frequency domain signal, which may be used in implementing the disclosed concept;

[0024] FIG. 8 is a schematic diagram showing the workflow for sensor deployment, signal analysis, and feature extraction according to an exemplary embodiment of the disclosed concept; and

[0025] FIG. 9, is a schematic diagram showing the CNN architecture and feature matrix for AI-based signal classification of an exemplary embodiment of the disclosed concept.

DETAILED DESCRIPTION OF THE INVENTION

[0026] As used herein, the singular form of “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

[0027] As used herein, the statement that two or more parts or components are “coupled” shall mean that the parts are joined or operate together either directly or indirectly, i.e., through one or more intermediate parts or components, so long as a link occurs.

[0028] As used herein, “directly coupled” means that two elements are directly in contact with each other.

[0029] As used herein, the term “number” shall mean one or an integer greater than one (i.e., a plurality).

[0030] As used herein, the terms “component” and “system” are intended to refer to a computer related entity, either hardware, a combination of hardware and software, software, or software in execution. For example, a component can be, but is not limited to being, a process running on a processor, a processor, an object, an executable, a thread of execution, a program, and/or a computer. By way of illustration, both an application running on a server and the server can be a component. One or more components can reside within a process and/or thread of execution, and a component can be localized on one computer and/or distributed between two or more computers.

[0031] As used herein, the term “quasi-distributed fiber optic sensing” shall mean sensing based on measurements of discrete sensor element(s) provided within or coupled to one or more fiber optic cables at a plurality of distinct locations to allow for measuring parameters both temporally and in a spatially distributed manner.

[0032] As used herein, the term “quasi-distributed fiber optic sensor” shall mean a fiber optic cable sensing device that employs quasi-distributed fiber optic sensing.

[0033] As used herein, the term “distributed fiber optic sensing” shall mean sensing parameters along the length of a fiber optic cable wherein the entire fiber optic cable acts as an array of sensing elements.

[0034] As used herein, the term “distributed fiber optic sensor” shall mean a fiber optic cable sensing device that employs distributed fiber optic sensing.

[0035] Directional phrases used herein, such as, for example and without limitation,

top, bottom, left, right, upper, lower, front, back, and derivatives thereof, relate to the orientation of the elements shown in the drawings and are not limiting upon the claims unless expressly recited therein.

[0036] The disclosed concept will now be described, for purposes of explanation, in connection with numerous specific details in order to provide a thorough understanding of the disclosed concept. It will be evident, however, that the disclosed concept can be practiced without these specific details without departing from the spirit and scope of this innovation.

[0037] The disclosed concept, as described herein, provides field inspection methods and sensor systems that can be used to defects or other undesired conditions on or within spent nuclear fuel storage canisters such as, without limitation, stress corrosion cracks in the canister or defects internal to the canister (e.g., defects to the fuel rods or fuel rod assembly within the canister or condensed water within the canister). In the exemplary embodiment, a combination of active and passive sensing techniques is employed as a structural health monitoring solution for multiple applications, providing complementary information about a cask storage system. Passive sensing differs from active sensing in that the former does not intentionally transfer energy into the structure under test. Rather, the sensors are deployed and monitored in pure detection mode and are used to collect data for structural health monitoring purposes. In the exemplary embodiment, quasi-distributed and/or distributed fiber optic sensors are arranged on the surface of the canister and are used to detect impacts of leaking gas inside the canister on the walls based upon passive sensing. In an additional exemplary embodiment, the quasi-distributed and/or distributed fiber optic sensors are arranged on the surface of the canister and are used to detect leakage of the canister walls. In a further additional exemplary embodiment, the quasi-distributed and/or distributed fiber optic sensors are arranged on the surface of the canister and are used to detect acoustic emission associated with the onset or further development of stress corrosion cracking. In addition, using an active sensing approach, corrosion damage on the surface of the canister itself may also be detected by scanning the entire canister surface by exciting the structure with acoustic waves such as, without limitation, conventional ultrasonic waves (used in, for example, conventional ultrasonic testing) or ultrasonic guided waves (UGWs), which are used in the illustrated exemplary embodiment. The same fiber sensor structure could be utilized for both the passive and active sensing, or alternatively, the monitoring could be accomplished using two separate fiber optic sensor installations. More traditional acoustic sensing technologies could also be included and considered for monitoring using the proposed approach, such as piezoelectric transducers. Additional sensing modalities could

include embodiments for which the temperature distribution is monitored over time, as an indicator of the current health of the fuel rod assembly. Static strain distribution can also be monitored over time, as an indicator of undesirable stresses and forces acting upon the canister which may ultimately increase the risk of structural degradation and failure.

[0038] FIG. 2 is a schematic diagram of a structural health monitoring (SHM) system 35 for inspection of nuclear waste storage canisters, such as canister 10, according to one non-limiting exemplary embodiment of the disclosed concept. SHM system 35 of the non-limiting exemplary embodiment is structured and configured to provide a dual-method approach for comprehensively monitoring the integrity of canister 10. The dual method includes a passive approach and an active approach, each of which is described herein. The passive method provides continuous monitoring for potential leaks, damage, or other threats, while the active method allows for periodic structural health assessments, enabling predictive health monitoring and lifetime prediction. This combined approach offers a more reliable and robust system for ensuring the safety and proper containment of spent nuclear fuel rods.

[0039] As seen in FIG. 2, SHM system 35 of the illustrated embodiment includes a guided wave pulser 40 that is coupled to an excitation coupling 45. Excitation coupling 45 is coupled to the top end of canister 10 and is a guided wave collar in the exemplary embodiment. As described in greater detail herein, guided wave pulser 40 and excitation coupling 45 together are structured and configured for use in the active method of the exemplary embodiment of the disclosed concept wherein ultrasonic guided waves (UGWs) are excited at the top of canister 10 and propagate across the entire canister surface towards the bottom of canister 10. In the illustrated embodiment, guided wave pulser 40 is structured and configured to provide an excitation signal as shown in FIG. 3A (time domain) and FIG. 3B (frequency domain). In the exemplary embodiment, the excitation signal is a 50 kHz, 5-period sinusoidal signal in the axial direction with a Hanning window. Also in the exemplary embodiment, guided wave pulser 40 provides cylindrically symmetric UGWs. It will be understood, however, that this is meant to be exemplary only and that other types of alternative transducer methods to excite other types of UGWs may also be employed.

[0040] Referring still to FIG. 2, SHM system 35 further includes a light source 50, such as a distributed feedback (DFB) laser. SHM system 35 also includes a fiber optic cable sensing device 55 that is coupled to and wrapped circumferentially around the outer surface of canister 10. Fiber optic cable sensing device 55 may be a quasi-distributed fiber optic sensor or a distributed fiber optic sensor for sensing parameters such as temperature, strain, or another acoustic parameter. As illustrated, fiber optic cable sensing device 55 of this

exemplary embodiment is a quasi-distributed fiber optic strain sensor that includes one or more sensing elements 60 provided therein (a so-called in-fiber sensing element) or coupled thereto. The one or more sensing elements 60 may be, for example and without limitation, a fiber Bragg grating (FBG), a Fabry-Perot interferometer, a Mach-Zehnder interferometer (MZI), a multimode interferometer (MMI), a piezoelectric sensor, an accelerometers, an acoustic emission sensor, or some combination thereof. Finally, SHM system 35 further includes a high-speed photodetector 65, a data acquisition (DAQ) unit 70 and a PC 75 with data processing systems/software stored therein in computer executable form, examples of which are described herein.

[0041] As noted above, the disclosed concept provides dual method monitoring. In the exemplary embodiment of the active method, in operation, UGWs are excited at the top of canister 10 by way of guided wave pulser 40 and excitation coupling 45. A number of alternative excitation scenarios may also be used in the disclosed concept. This can include UGWs at different locations as well as a single point excitation source or a number of sensors at multiple locations. The UGWs propagate across the surface of canister 10 from top to the bottom. However, due to wave dispersion and reflections from both ends of canister 10, the initial signal applied to canister 10 is decomposed into several different modes of wave packets propagating over canister 10. In addition, at the same time, light from light source 50 is propagated into fiber optic cable sensing device 55 in order to enable fiber optic cable sensing device 55, which in the illustrated embodiment comprises a strain sensor, to measure the strain that is caused in canister 10 by the UGWs. More specifically, the light that is transmitted through fiber optic cable sensing device 55 (and/or reflected by fiber optic cable sensing device 55 in an alternate implementation) is indicative of the strain being experienced by canister 10, and that light is detected by photodetector and responsive signals are provided to DAQ 70 and PC 75 for processing thereby as described herein.

[0042] In the exemplary embodiment, the strain signal(s) received in PC 75 from canister 10 as just described are analyzed and compared to stored strain signals for an undamaged container to assess the interference on the UGWs that is caused by any damage in container 10. This interference can be analyzed and further processed in the time and frequency domains to obtain valuable information about the location, type, and size of any damage of or to container 10.

[0043] In one particular implementation, the signal(s) that are received in PC 75 are indicative of a circumferential strain value contour of canister 10. The circumferential strain value contour is a measurement of the strain that occurs in fiber optic cable sensing device

55. This strain is caused by the deformation and vibration of canister 10, and it is measured using fiber optic cable sensing device 55. Specifically, the strain measured along the axis of fiber optic cable sensing device 55 corresponds to the circumferential strain of canister 10. Circumferential displacement, which is a related parameter that may be determined, is a measurement of the movement of the canister in the circumferential direction, also caused by the deformation and vibration. These measurements can be used to detect corrosion in canister 10 by comparing the values obtained from a healthy canister with those obtained using SHM 35. In exemplary embodiments, the active method may analyze changes in wave propagation, wave attenuation, or wave speed to detect corrosion or structural issues within canister 10. The active method may also use data visualization tools, like circumferential strain value contour plots and displacement maps, to help identify problematic regions within the walls of canister 10. Static strain and dynamic strain data (e.g., vibrations, acoustics) would be included for this type of a characterization. Pattern recognition and machine learning techniques may also be used. Such processing tools and techniques may be implemented in/by a controller of PC 75 (or another suitable computing device) as one or more components thereof by the way of a number of computer executable software routines.

[0044] For the passive method, degradation modes, such as fuel rod assembly leakages or canister wall leakages, have the potential to cause a high-speed jet of helium or other gases to leak within/around canister 10. When the leakage is significant enough from the internal fuel rod assembly, it can impinge on the walls of canister 10 or on the walls of the fuel rod assembly with enough force to induce a significant transient vibration response. An additional degradation mode, stress corrosion cracking, will also produce acoustic emission signatures which can be monitored in real time without requiring an active source. Depending upon the details of the acoustic emission signature, localization and classification (type, size, number) can also be accomplished by the advanced data processing discussed in subsequent sections. Thus, in the passive method of the disclosed concept, measurements are made by fiber optic cable sensor 55 without the excitation of UGWs as described above. The signal(s) from fiber optic cable sensor 55 are provided to PC 75 in the manner described above. PC 75 may then employ signal processing techniques, such as filtering, signal amplification, and feature extraction, to analyze the sensor data to detect damages such as leaks and stress corrosion cracking. In exemplary embodiments, the passive method may use pattern recognition algorithms or machine learning techniques to identify the presence of leaks or damage based on the characteristics of the sensed signals. Such processing tools and techniques may be implemented in/by a controller of PC 75 (or another suitable computing

device) as one or more components thereof by the way of a number of computer executable software routines.

[0045] As noted elsewhere herein, the same fiber sensor structure could be utilized for both the passive and active sensing. This is the case in the illustrated embodiment shown in FIG. 2, wherein fiber optic cable sensing device 55 is used separately in the active and passive methods. This is meant to be exemplary only, and it will be understood that the monitoring could be accomplished using two separate fiber optic sensor installations, namely one fiber optic cable sensor 55 for the active method and a separate fiber optic cable sensor 55 for the passive method (both being coupled to photodetector 65, DAQ 70 and PC 75).

[0046] Furthermore, in the FIG. 2 embodiment described above, fiber optic cable sensing device 55 is wrapped circumferentially around the outer surface of canister 10. Such an implementation is meant to be exemplary only, and alternative configurations are contemplated within the scope of the disclosed concept. For example, an alternative configuration is shown in FIG. 4, which illustrates an alternative SHM system 35'. In FIG. 4, like parts are labeled with like reference numerals. As seen in FIG. 4, in this exemplary embodiment, fiber optic cable sensing device 55 is disposed along the longitudinal axis of canister 10. Another alternative configuration is shown in FIG. 5, which illustrates a further alternative SHM system 35''. In FIG. 5, like parts are labeled with like reference numerals. As seen in FIG. 5, in this exemplary embodiment, fiber optic cable sensing device 55 is disposed spirally around the outer surface of canister 10.

[0047] Moreover, in the FIG. 2, FIG. 4 and FIG. 5 embodiments, a single fiber optic cable sensing device 55 is employed. FIG. 6 is an illustration of a further alternative SHM system 35''' in which a plurality of fiber optic cable sensing devices 55 are provided (e.g., circumferentially) on/around the outer surface of canister 10 in order to provide quasi-distributed fiber optic sensing. As seen in the FIG. 6 exemplary embodiment, those separate devices are spaced apart along the longitudinal axis of canister 10. Such multiple fiber-optic coupling devices 55 are each structured to receive the light from light source 50 by way of 1 X N optical coupler 80. The outputs of the multiple fiber optic cable sensing devices 55 are provided to a 1 X N optical switch 85, which is able to selectively provide the signals from the devices to detector 65, DAQ 70 and PC 75 for processing as described herein. Furthermore, in an alternative implementation, rather than having a single photodetector 65 and 1 X N optical switch 85, a system may include N photodetectors 65, each one coupled to a respective one of the fiber optic cable sensing device 55, with the outputs of the photodetectors 65 being provided to DAQ 70.

[0048] A number of exemplary processing techniques and components that may be used to implement the processing of the disclosed concept will now be described. (i.e., the processing of the sensor signal(s) to identify and/or classify damage). Those exemplary processing techniques include techniques based on feature extraction, and techniques based on machine learning using a convolutional neural network (CNN) for AI-based signal classification. Each of the techniques described herein may be implemented in/by a controller of PC 75 (or another suitable computing device) as one or more components thereof by the way of a number of computer executable software routines.

[0049] The feature extraction based approach involves the extraction of various quantitative features from the measured sensor signals and their comparison across different types, sizes, and locations of defects in canisters such as canister 10. In the exemplary embodiment, the emphasis is placed on extracting defect-related features as damage indicators. Physics-based models, such as finite element analysis, may also be used to simulate the impact of various defects and features for assistance with improving the ability to classify features of signals. Additional embodiments may further employ AI-based classification based on extracted features. The primary objective of feature extraction is to enhance the method's performance in detecting, localizing, and classifying defects. The application of statistical features from vibration or ultrasonic signals has been proven successful in damage detection through more traditional acoustic non-destructive evaluation (NDE) methods. This success fosters confidence in the applicability of these methods with distributed acoustic sensing (DAS) based interrogation techniques.

[0050] An exemplary implementation of such feature extraction based techniques is described in connection with FIG. 7, which shows feature extraction from a time domain and a frequency domain signal. As shown in FIG. 7 and in the Table 1 below, in the active monitoring method, the received signal is divided into three-time domain windows: "excitation signal," "defect echo signal," and "boundary reflection wave" mode.

Active method		
Wave-group time window	Feature Category	
	Time domain feature	Frequency domain feature
Excitation	1. Amplitude 2. Signal duration 3. Signal arrival time	1. Dominant frequency components 2. Spectral energy distribution 3. Bandwidth
Defect echo		
Boundary reflection		
Passive method		
	Feature Category	

	Time domain feature	Frequency domain feature
Leak/Stress corrosion cracking	1. Signal amplitude 2. Signal duration 3. Signal arrival time 4. Acoustic emission event rate (the number of events detected per unit of time.)	1. Dominant frequency components 2. Spectral energy distribution 3. Bandwidth

TABLE 1

[0051] To analyze the signals obtained from both the active and passive methods, the disclosed concept employs feature extraction techniques in both the time and frequency domains. In particular, for each of the three-time domain windows, the process of extracting features involves the following steps:

1. Time Domain Analysis and Feature Extraction:

[0052] First, analyze the time-domain signals for the “excitation signal,” “defect echo signal,” and “boundary reflection wave”. Then perform statistical analysis on each signal and extract relevant features such as amplitude, signal duration, arrival time, and other time-domain characteristics that may provide insights into the presence, location, and size of defects or damage.

2. Frequency Domain Analysis:

[0053] Transform the time-domain signals for the “excitation signal,” “defect echo signal,” and “boundary reflection wave” into the frequency domain using Short Time Fourier Transform (STFT). This transformation allows for the analysis of signal characteristics in the frequency domain, which can reveal information about the underlying structure of the canister and potential defects.

3. Feature Extraction from Frequency Domain Signals:

[0054] Analyze the frequency-domain signals obtained from the STFT and extract relevant features. These features may include dominant frequency components, spectral energy distribution, bandwidth, and other frequency-domain characteristics that can provide valuable information about the canister's health and potential defects.

4. Feature Combination and Analysis:

[0055] Combine the extracted features from both time and frequency domains for the “excitation signal,” “defect echo signal,” and “boundary reflection wave” of the L(0,2) mode.

Analyze these combined features to detect, localize, and classify defects or damage in the nuclear waste storage canisters.

[0056] For the passive monitoring method, a comparable feature extraction process is employed on the signals acquired from the sensors. The time-domain signal can be divided into multiple time windows, with each time window undergoing a transformation to the frequency domain. The extracted features from both active and passive methods serve as input for a convolutional neural network (CNN) classification model, which offers insights into the location, type, and size of the defects or damage. By employing feature extraction techniques in both time and frequency domains for the active and passive methods, this approach enhances the monitoring capabilities and provides valuable insights into health of a canister, such as canister 10, contributing to ensuring the safety and proper containment of spent nuclear fuel rods.

[0057] Once the relevant features are extracted from the time and frequency domains, the disclosed concept may utilize a trained CNN for classification. Although the most robust method for processing and analysis of guided ultrasonic acoustic wave data would involve extensive training of an AI or machine learning model using the full set of data to allow for localization and classification, the exemplary embodiment focuses on CNN classification using the extracted defect-related features.

[0058] The exemplary embodiment employing a CNN is described below in connection with FIG. 8, which shows the workflow for sensor deployment, signal analysis, and feature extraction of this exemplary embodiment, and FIG. 9, which shows the CNN architecture and feature matrix for AI-based signal classification of this exemplary embodiment.

[0059] The AI-based signal classification process of the non-limiting exemplary embodiment employs a CNN to analyze the extracted features from the sensor data. The workflow consists of three main steps, as illustrated in FIG. 8. The first step is a sensor deployment step wherein a number of sensors, such as fiber optic cable sensor devices 55, are strategically placed on the nuclear waste storage canister, such as canister 10, to capture the relevant signals for analysis. The next step is a time domain and frequency domain signal analysis step, wherein the acquired signals are analyzed in both the time and frequency domains, enabling the extraction of relevant features that indicate the presence, location, and size of defects or damage. This dual approach is critical as it allows for the comprehensive characterization of signals, aiding in the detection of unique features associated with defects or damage, such as their presence, location, and dimensions. The last step is a feature

extraction and mapping feature matrix step. In this step the features identified during the time and frequency domain analyses are aggregated into a structured form, typically known as a feature matrix. This matrix encapsulates the key attributes of the signals and serves as input to an advanced machine learning (ML) model. In the exemplary embodiment, the feature matrix serves as input to the CNN model. Alternatively, the input to the CNN model can simply be time series data as a function of position. While the exemplary embodiment describes the use of a CNN, it is understood that the approach is not confined to this specific model. Various other machine learning models, such as Support Vector Machines (SVMs), Random Forests, or even more complex Deep Learning architectures like Recurrent Neural Networks (RNNs), can be employed depending on the nature of the data and the specific requirements of the task. In some cases, the input to the ML model can also be simplified to raw time series data as a function of position. This flexibility allows the chosen ML model to be adapted to the most informative representation of the data, whether it is in raw or processed form.

[0060] FIG. 9 depicts the feature matrix as input to the CNN network of this exemplary embodiment. In this embodiment, the CNN is a multi-layer CNN model including two sets of convolutional and pooling layers followed by fully connected layers for classification. The multi-layer CNN model of this exemplary embodiment is designed for signal classification, with the input data being a 2D tensor of size (batch size, N, M). Here, N is the number of sensor channels deployed on canister 10 and M depends on the feature(s) extract from the received signal(s). As seen in FIG. 9, the network architecture consists of the following layers: (i) two convolutional layers with 16 and 32 filters, respectively, and a kernel size of 10, (ii) a max pooling layer with a pool size of 2 following each of the convolutional layers to reduce the spatial dimensions of the feature maps, (iii) two fully connected layers with 64 and 6 neurons, respectively, which serve as the output layer for multi-class classification, and (iv) a softmax activation function applied to the output layer for transforming the output into probability scores for each class. In the exemplary embodiment, the CNN model is trained using categorical cross-entropy loss and a selected optimizer with a learning rate of 0.001 and a batch size of 32. The training process involves feeding the feature matrix into the network and adjusting the weights iteratively to minimize the loss function. Once trained, the CNN model can be used to classify the health of a canister, such as canister 10, based on the extracted features, providing valuable information about the location, type, and size of the defects or damage.

[0061] In short, in this aspect, the disclosed concept includes the AI training process

using a CNN for signal classification. The model takes the feature matrix derived from sensor data as an input and is trained to classify canister health based on the extracted features. This AI-based approach enhances the monitoring capabilities and provides valuable insights into the canister's health, contributing to ensuring the safety and proper containment of spent nuclear fuel rods.

[0062] While specific embodiments of the invention have been described in detail, it will be appreciated by those skilled in the art that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure.

Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of disclosed concept which is to be given the full breadth of the claims appended and any and all equivalents thereof.

What is claimed is:

1. A system for monitoring structural health of a storage canister for storing spent nuclear fuel, comprising:
 - a wave assembly structured and configured for exciting the canister with acoustic waves;
 - a number of sensor assemblies coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices;
 - a light source structured and configured for providing interrogation light to the number of sensor assemblies;
 - a detector coupled to the number of sensor assemblies, the detector being structured and configured for receiving a first output of the number of sensor assemblies responsive to the interrogation light in an active mode of operation while the canister is being excited with acoustic waves, and in response thereto generating active sensor data, and the detector also being structured and configured for receiving a second output of the number of sensor assemblies responsive to the interrogation light in a passive mode of operation while the canister is not being excited with the acoustic waves, and in response thereto generating passive sensor data; and
 - a controller coupled to the detector, the controller being structured and configured for receiving the active sensor data and the passive sensor data, and for analyzing either or both of the active sensor data and the passive sensor data and detecting a defect or other undesired condition of the canister or internal to the canister based on the analyzing.
2. The system according to claim 1, wherein the wave assembly is an ultrasonic guided wave assembly structured and configured for exciting the canister with ultrasonic guided waves.
3. The system according to claim 1, wherein the number of sensor assemblies include a number of first sensor assemblies for generating the first output and the active sensor data, and a number of second sensor assemblies for generating the second output and the passive sensor data.
4. The system according to claim 1, wherein the sensor assemblies used to generate the first output and the active sensor data are the same as the sensor assemblies used to generate the second output and the passive sensor data.

5. The system according to claim 1, wherein the analyzing comprises extracting a number of features from either or both of the active sensor data and the passive sensor data and detecting the defect of the canister based on the number of features.

6. The system according to claim 5, wherein the extracting the number of features includes extracting a number of first features in a time domain and a number of second features a frequency domain.

7. The system according to claim 5, wherein the extracting the number of features from either or both of the active sensor data and the passive sensor data comprises dividing either or both of the active sensor data and the passive sensor data into three time domain windows including an excitation signal, a defect echo signal and a boundary reflection wave signal, and wherein the number of features comprise one or more time domain features and one or more frequency domain features.

8. The system according to claim 7, wherein the time domain features include one or more of amplitude, signal duration and signal arrival time and the frequency domain features include one or more of dominant frequency components, spectral energy distribution, and bandwidth.

9. The system according to claim 7, wherein the extracting the number of features from either or both of the active sensor data and the passive sensor data further comprises converting the time domain windows to frequency domain windows.

10. The system according to claim 6, wherein the controller implements a machine learning system for analyzing either or both of the active sensor data and the passive sensor data and detecting the defect or other undesired condition of the canister or internal to the canister based on the analyzing, wherein the analyzing is based on the number of first features and the number of second features.

11. The system according to claim 10, wherein the machine learning system comprises a trained convolutional neural network (CNN), wherein the analyzing comprises mapping the number of first features and the number of second features into a feature matrix,

and providing the feature matrix to the CNN as an input, the CNN being trained to classify defects or other undesired conditions based on the feature matrix.

12. The system according to claim 1, wherein the analyzing comprises analyzing either or both of the active sensor data and the passive sensor data by comparing either or both of the active sensor data or the passive sensor data to stored data for an undamaged canister.

13. The system according to claim 1, wherein the analyzing comprises analyzing either or both of the active sensor data and the passive sensor data by comparing either or both of the active sensor data or the passive sensor data to a physics based model of the canister or a digital twin of the canister.

14. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of strain sensors, and wherein the analyzing comprises generating a circumferential strain value contour based on either or both of the active sensor data and the passive sensor data that is used in detecting the defect or other undesired condition.

15. The system according to claim 1, wherein each of a number of the fiber optic cable sensing devices is a quasi-distributed fiber optic sensor.

16. The system according to claim 1, wherein each of a number of the fiber optic cable sensing devices is a distributed fiber optic sensor.

17. A method of monitoring structural health of a storage canister for storing spent nuclear fuel, the method comprising:

selectively exciting the canister with acoustic waves, wherein a number of sensor assemblies are coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices;

receiving a first output of the number of sensor assemblies responsive to interrogation light in an active mode of operation while the canister is being excited with the acoustic waves, and in response thereto generating active sensor data, and receiving a second output of the number of sensor assemblies responsive to interrogation light in a passive mode

of operation while the canister is not being excited with the acoustic waves, and in response thereto generating passive sensor data; and

analyzing in a controller either or both of the active sensor data and the passive sensor data and detecting a defect or other undesired condition of the canister or internal to the canister based on the analyzing.

18. The method according to claim 17, further comprising coupling the number of sensor assemblies to the exterior surface of the canister.

19. The method according to claim 17, wherein the acoustic waves are ultrasonic guided acoustic waves.

20. The method according to claim 17, wherein the analyzing comprises extracting a number of features from either or both of the active sensor data and the passive sensor data and detecting the defect of the canister based on the number of features.

21. The method according to claim 20, wherein the extracting the number of features includes extracting a number of first features in a time domain and a number of second features a frequency domain.

22. The method according to claim 21, wherein the extracting the number of features from either or both of the active sensor data and the passive sensor data comprises dividing either or both of the active sensor data and the passive sensor data into three time domain windows including an excitation signal, a defect echo signal and a boundary reflection wave signal, and wherein the number of features one or more time domain features and one or more frequency domain features.

23. The method according to claim 22, wherein the time domain features include one or more of amplitude, signal duration and signal arrival time and the frequency domain features include one or more of dominant frequency components, spectral energy distribution, and bandwidth.

24. The method according to claim 22, wherein the extracting the number of features from either or both of the active sensor data and the passive sensor data further comprises converting the time domain windows to frequency domain windows.

25. The method according to claim 21, wherein the controller implements a machine learning system for analyzing either or both of the active sensor data and the passive sensor data and detecting the defect or other undesired condition of the canister or internal to the canister based on the analyzing, wherein the analyzing is based on the number of first features and the number of second features.

26. The method according to claim 25, wherein the controller implements a trained convolutional neural network (CNN), wherein the analyzing comprises mapping the number of first features and the number of second features into a feature matrix, and providing the feature matrix to the CNN as an input, the CNN being trained to classify defects based on the feature matrix.

27. The method according to claim 17, wherein the analyzing comprises analyzing either or both of the active sensor data and the passive sensor data by comparing either or both of the active sensor data or the passive sensor data to stored data for an undamaged canister.

28. The method according to claim 17, wherein the analyzing comprises analyzing either or both of the active sensor data and the passive sensor data by comparing either or both of the active sensor data or the passive sensor data to a physics base model of or a digital twin of the canister.

29. The method according to claim 17, wherein the fiber optic cable sensing devices include a number of strain sensors, and wherein the analyzing includes generating a circumferential strain value contour based on either or both of the active sensor data and the passive sensor data that is used in detecting the defect.

30. The method according to claim 17, wherein the fiber optic cable sensing devices include a number of temperature sensors.

31. The method according to claim 17, wherein the fiber optic cable sensing devices include a number of strain sensors.

32. The method according to claim 17, wherein the fiber optic cable sensing devices include a combination of a number of strain sensors and a number of temperature sensors.

33. The method according to claim 17, wherein the fiber optic cable sensing devices include a number of temperature sensors and a number of acoustic sensors not configured for sensing strain or temperature.

34. The method according to claim 17, wherein the fiber optic cable sensing devices include a number of strain sensors and a number of acoustic sensors not configured for sensing strain or temperature.

35. The method according to claim 17, wherein the fiber optic cable sensing devices include a number of temperature sensors, a number of strain sensors, and a number of acoustic sensors not configured for sensing strain or temperature.

36. A computer program product, comprising a non-transitory computer usable medium having a computer readable program code embodied therein, the computer readable program code being adapted to be executed to implement a method of monitoring structural health of a storage canister for storing spent nuclear fuel as recited in claim 17.

37. A method of monitoring structural health of a storage canister for storing spent nuclear fuel, the method comprising:

exciting the canister with acoustic waves, wherein a number of sensor assemblies are coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices;

providing interrogation light to the number of sensor assemblies in an active mode of operation while the canister is being excited with the acoustic waves;

receiving a first output of the number of sensor assemblies responsive to the interrogation light and in response thereto generating active sensor data; and

analyzing in a controller the active sensor data and detecting a defect or other undesired condition of the canister or internal to the canister based on the analyzing.

38. A method of monitoring structural health of a storage canister for storing spent nuclear fuel, wherein a number of sensor assemblies are coupled to an exterior surface of the canister, each of the sensor assemblies including one or more fiber optic cable sensing devices, the method comprising:

providing interrogation light to the number of sensor assemblies in a passive mode of operation while the canister is not being excited with acoustic waves;

receiving a first output of the number of sensor assemblies responsive to the interrogation light, and in response thereto generating passive sensor data; and

analyzing in a controller the passive sensor data and detecting a defect or other undesired condition of the canister or internal to the canister based on the analyzing.

39. The method according to claim 38, wherein the method is for passively monitoring the canister for stress corrosion cracking, wherein the analyzing and detecting comprises localizing and classifying the defect.

40. The method according to claim 39, wherein the fiber optic cable sensing devices include a number of temperature sensors, a number of strain sensors, a number of acoustic sensors not configured for sensing strain or temperature, or any combination thereof.

41. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of temperature sensors.

42. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of strain sensors.

43. The system according to claim 1, wherein the fiber optic cable sensing devices include a combination of a number of strain sensors and a number of temperature sensors.

44. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of temperature sensors and a number of acoustic sensors not configured for sensing strain or temperature.

45. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of strain sensors and a number of acoustic sensors not configured for sensing strain or temperature.

46. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of temperature sensors, a number of strain sensors, and a number of acoustic sensors not configured for sensing strain or temperature.

47. The system according to claim 38, wherein the system is for passively monitoring the canister for stress corrosion cracking, wherein the controller is structured and configured for analyzing the passive sensor data to localize and classify the defect.

48. The system according to claim 1, wherein the fiber optic cable sensing devices include a number of temperature sensors, a number of strain sensors, a number of acoustic sensors not configured for sensing strain or temperature, or any combination thereof.

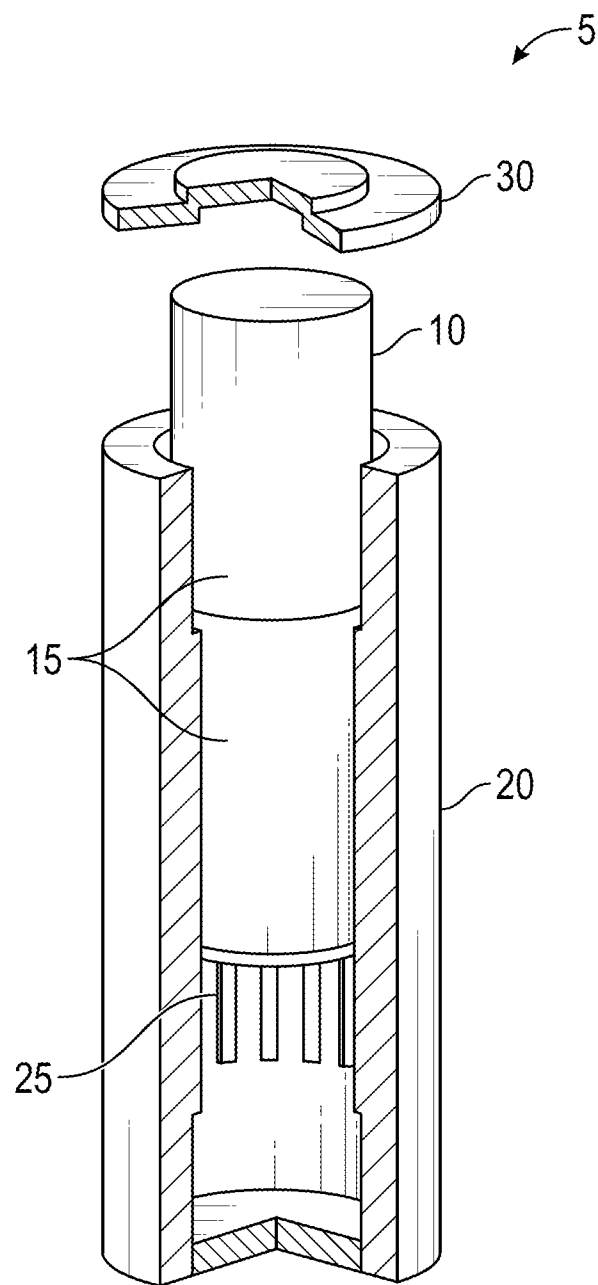


FIG. 1
(Prior Art)

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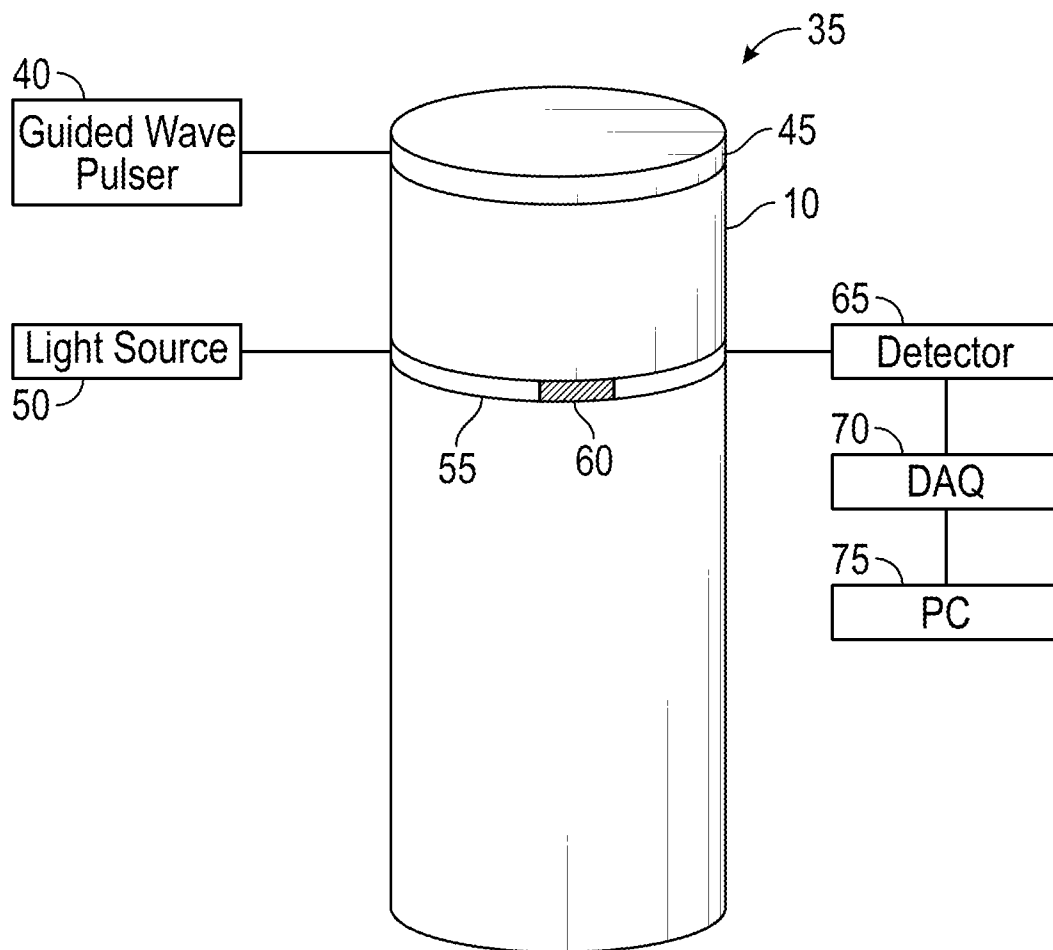
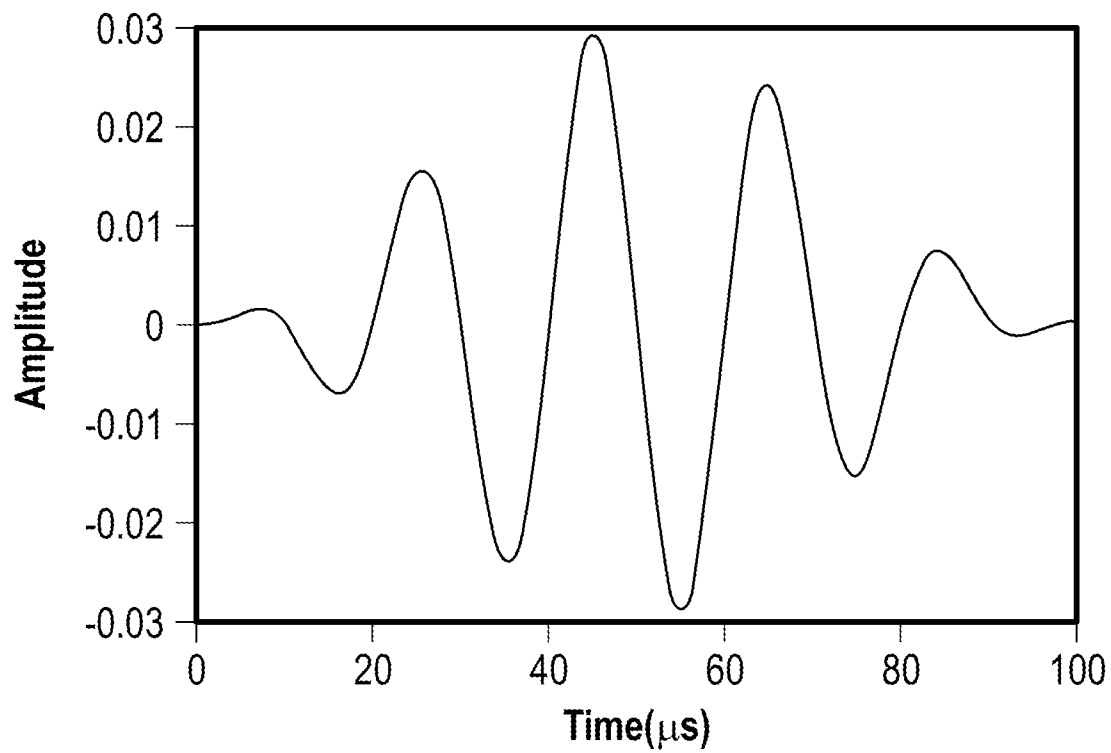
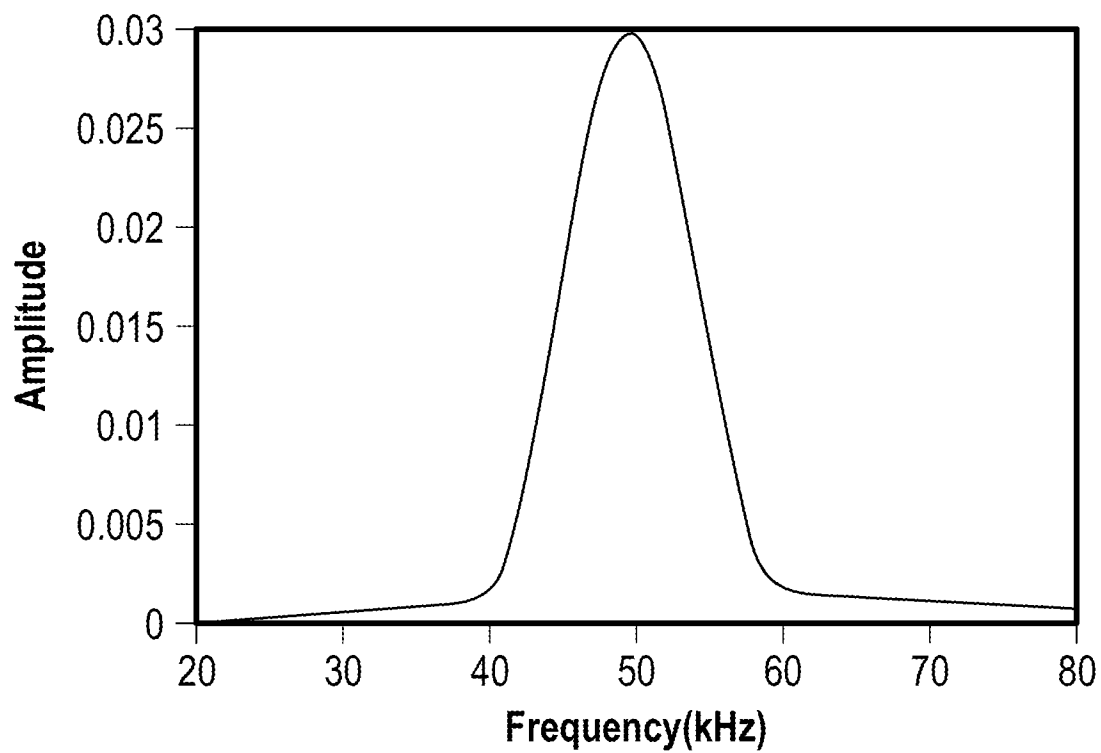


FIG. 2

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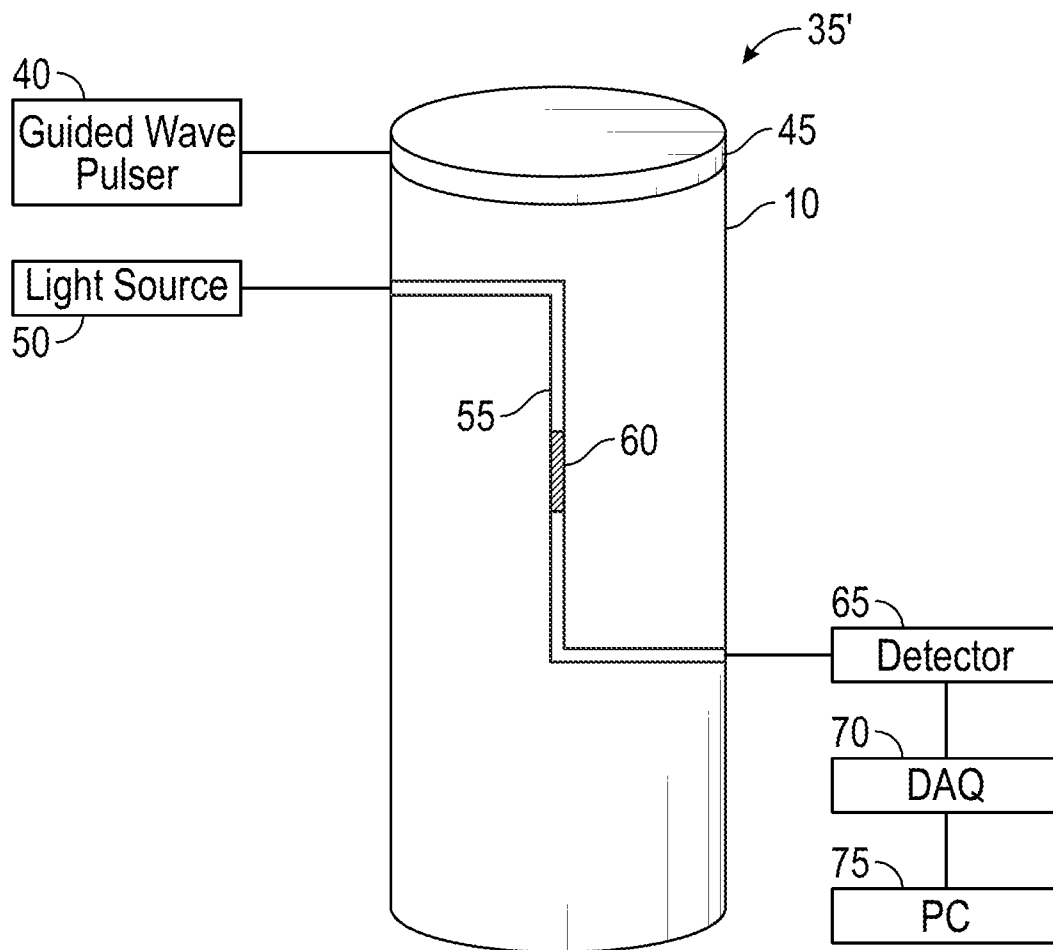


FIG. 4

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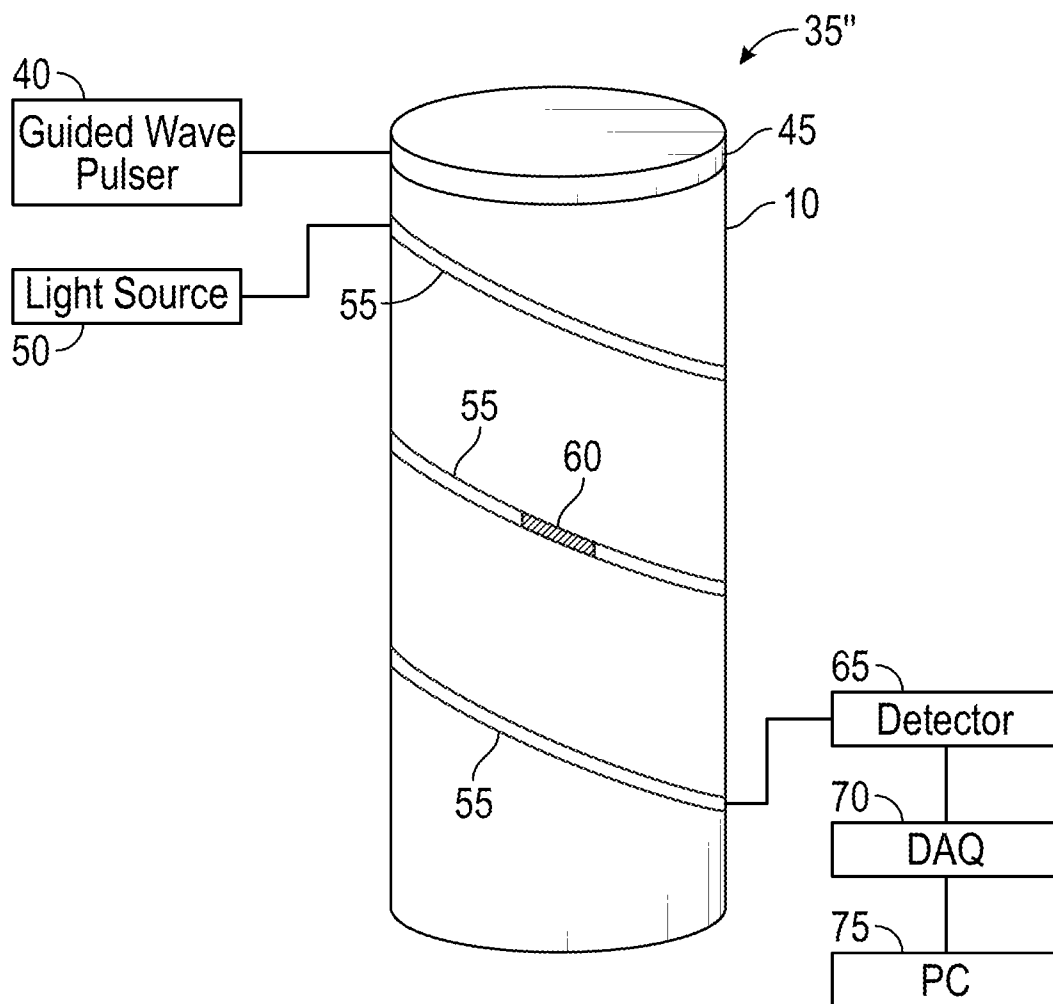


FIG. 5

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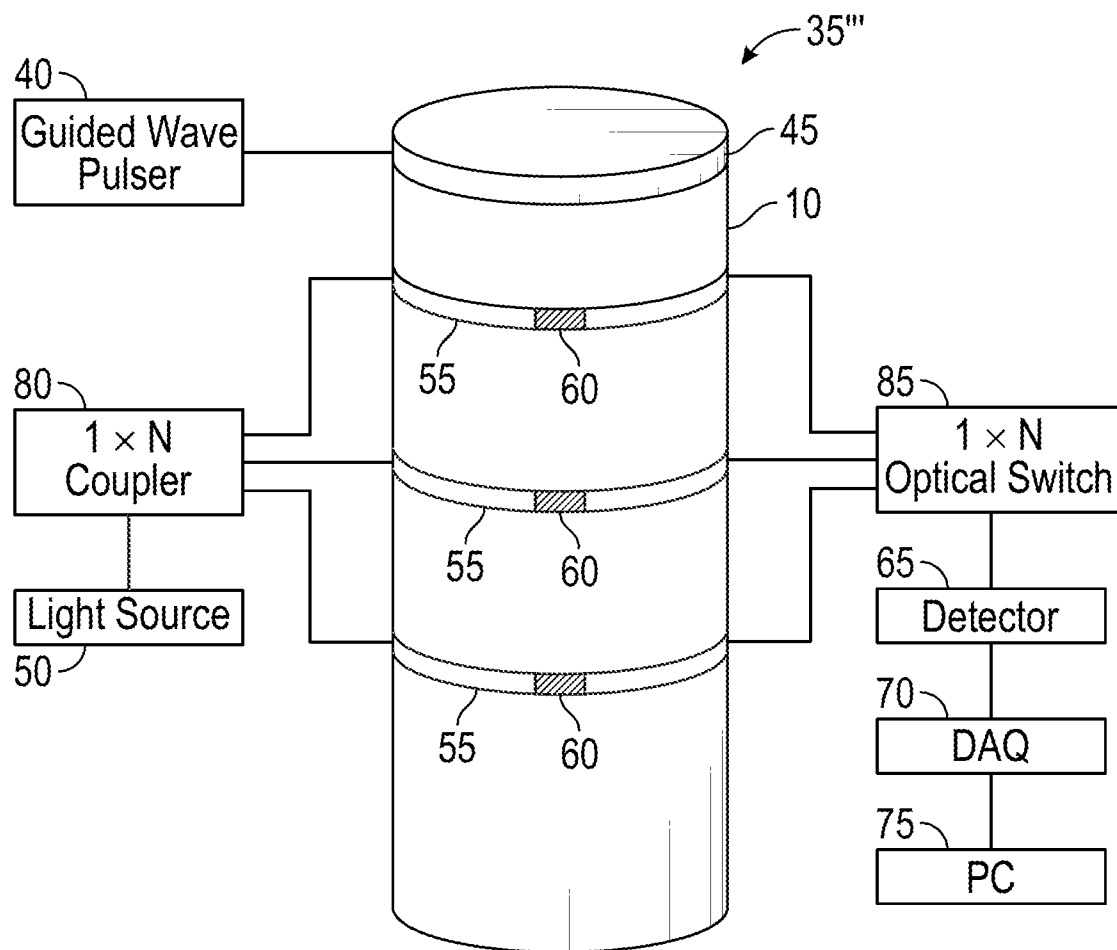


FIG. 6

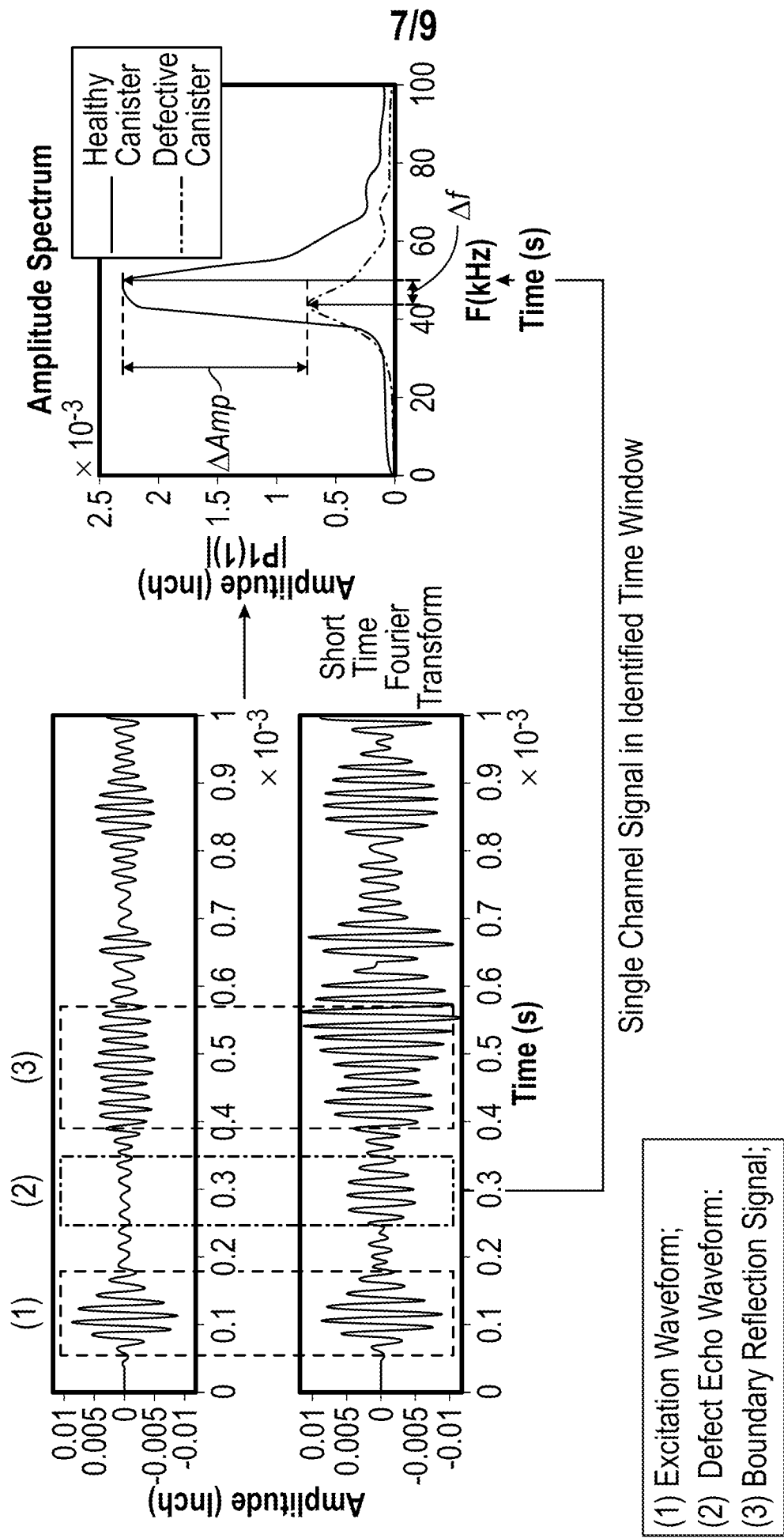


FIG. 7

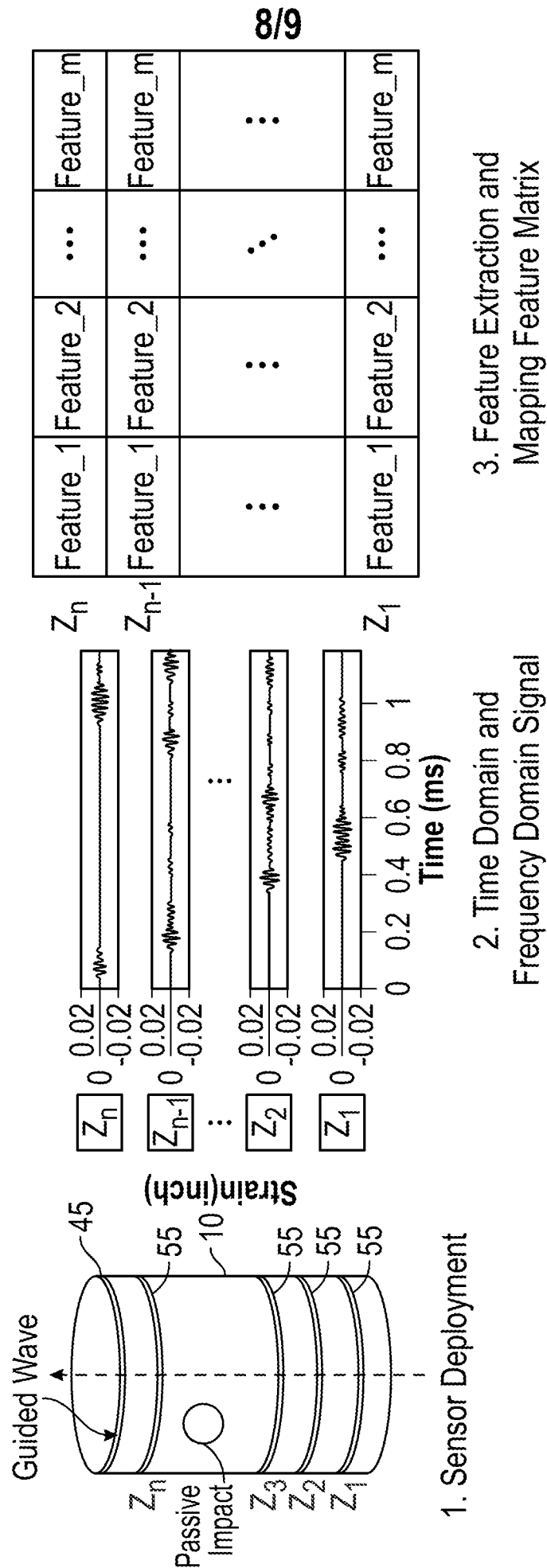


FIG. 8

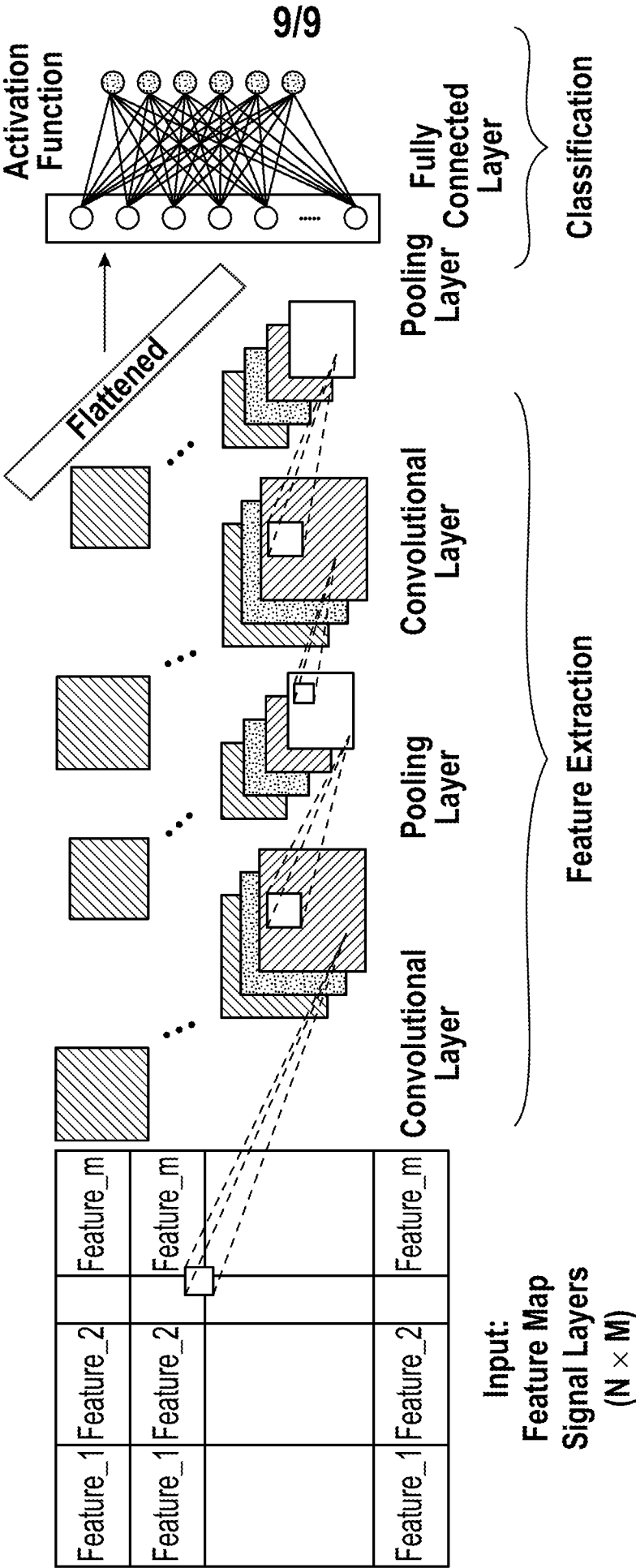


FIG. 9