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(54) Title: STRUCTURAL HEALTH MONITORING OF WIND TURBINE BLADES USING WIRELESS ACOUSTIC SENSING

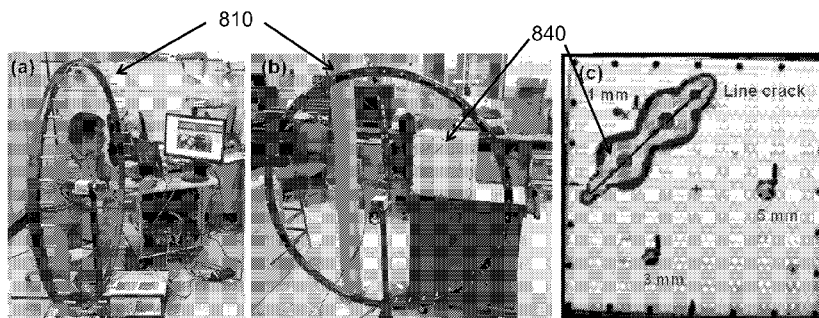


FIG. 8A

FIG. 8B

FIG. 8C

(57) **Abstract:** Systems and methods for detecting damage or defects in wind turbine blades are described. In one embodiment, a sound receiver interior to the blade is used to listen for noise that is associated with the presence of damage or defects that interact with air flowing over the exterior of the blade. In another embodiment, a sound source located within the blade generates sound that is received by one or more sound receivers external to the blade. The received sounds are communicated wirelessly to a data processing system that analyzes the sound data. The results can be recorded, displayed, or transmitted for further processing. The systems have detected cracks and holes as small as one millimeter in diameter. One advantage of the system is that it makes possible preventive maintenance on an as needed or preplanned (scheduled) basis, rather than as an emergency response to turbine blade failure.

STRUCTURAL HEALTH MONITORING OF WIND TURBINE BLADES USING
WIRELESS ACOUSTIC SENSING
CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to and the benefit of co-pending U.S. provisional patent application Serial No. 61/896,315, filed October 28, 2013, which application is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The invention relates to wind turbines in general and particularly to systems for and methods of identifying damage and defects in turbine blades.

BACKGROUND OF THE INVENTION

[0003] One of the fundamental challenges of our generation is the creation and use of sustainable forms of clean energy. As of 2013, the wind turbine installations in the U.S. had a power generating capability exceeding 61 gigawatts while providing 4.1% of the nation's electricity. Approximately 20 years ago, the largest wind turbines that generated approximately 50 kW of electricity per unit had blades 8-m long. Today the largest mass-produced blades in the world are approximately 75-m long, and are used in systems that generate approximately 6 MW per unit, which is enough electricity to supply 6,000 typical households.

[0004] Although a wind turbine's nacelle is usually instrumented with numerous sensors and easily monitored, the blades generally contain few to no sensors. Wind turbine blade failures can be initiated by several factors at multiple locations. Therefore, a current area of interest to the wind industries is how to monitor the condition of blades over a large area while not adding significant cost or affecting the performance of the structure.

[0005] The land-based wind resource within the U.S. is abundant, is underutilized, and can supply more than ten times the nation's current electrical needs. A significant limitation that restricts the widespread adoption of wind energy globally is the cost of energy compared to fossil fuels. One primary factor that contributes to the cost of clean-wind energy is reliability and being able to comprehensively monitor the condition of wind turbines to

improve energy capture and predict premature failure. The present state of the art is the visual inspection of rotor blades or by using acceleration sensors that cannot effectively diagnose or localize damage.

[0006] Wind turbines operate autonomously and can possess reliability issues attributed to manufacturing defects, fatigue failure, or extreme weather events. In particular, wind turbine blades can suffer from leading and trailing edge splits, holes, or cracks that can lead to blade failure and loss of efficiency and energy revenue generation.

[0007] Turbine reliability and unanticipated failure is a major cost driver for the wind energy industry and is ultimately responsible for reduced power generation and excessive repair costs that raise the cost of wind generated energy. FIG. 1A through FIG. 1H illustrate some of the problems that occur when wind turbine systems suffer damage. FIG. 2A through FIG. 2G illustrate examples of damage to rotor blades and how damage may be detected using contacting strain or conductive sensors.

[0008] For most installed wind turbines, monitoring systems are not effectively utilized because systems do not exist to monitor specific components, and are too costly to implement. Many turbines that have been installed do not include component monitoring systems. Most turbines do not have any kind of blade monitoring system and they are not currently effective in damage detection (e.g. erosion, holes, cracks, delamination, leading and trailing edge splits).

[0009] Currently, existing inspection techniques are predominantly geared towards non-destructive testing and evaluation of cavity structures in their disassembled state (component level rather than system level) and are primarily used for detecting defects and deviations in tolerance within a manufacturing setting. The traditional sensing approaches (e.g., strain-gage networks, acoustic emission sensors, fiber optic cables, ultrasonic, laser-Doppler sensing, and piezoelectric transducers) heavily depend on contact-type measurement sensor arrays that are either difficult to instrument, challenging to maintain, unreliable, costly, ineffective in identifying and localizing distributed damage, or are impractical to be implemented in service.

[0010] Predominantly passive acoustic sensing approaches for damage detection of structures have been previously investigated where the structure being investigated generates structural noise and vibration under the influence of its own operational state. These techniques generally employ a microphone to observe the healthy state of operation forming a

baseline. Then, when a change in the radiated acoustic noise is detected, the change in the acoustic signature may be correlated to the damage in the structure. However, in most cases the approaches are not effective because the radiated noise is generally masked by the background flow induced noise, leading to poor signal to noise ratios that are below the threshold necessary for detection. Acoustic sensing, when used in its passive form, is also challenging due to the influence of extraneous unwanted noise radiated by other complicated acoustic sources that reduce the signal to noise ratio ultimately masking the sound content of interest necessary for detection. The reduced signal to noise ratio decreases the dependability of acoustic measurements that are used for decision making for fault diagnostics or damage detection. Moreover, investigations in the literature that have explored the applicability of using audible frequency range signals for damage detection are very limited.

[0011] Although wind turbine environmental noise has historically been of great interest, only recently has beamforming been used to identify the sound radiated from operating wind turbines for structural health monitoring. FIG. 3A-FIG.3D(Figure 1a) shows an example of beamforming performed on a 52 m diameter, 65 m high, Gamesa wind turbine during operation where the primary source of sound characterized is that caused by the flow induced noise.

[0012] The acoustic beamforming technique has been widely used in many applications including source localization, spatial filtering, echo cancellation, noise reduction and many others. More recently, the approach has been used to identify the sound radiated from operating wind turbine blades with limited success because the primary source of sound is caused by the flow induced noise. Although wind turbine environmental noise has historically been of great interest, only recently has acoustic sensing and acoustic beamforming been used to identify the sound radiated from operating wind turbines for structural health monitoring with limited success. The biggest challenge that has limited the application of the technique for damage identification is attributed to the dominant aerodynamic noise levels masking the variations in the acoustic radiation due to defects and damage.

[0013] Acoustic beamforming is a method for processing data acquired by a microphone array to produce visual images that represent the distribution of the acoustic source radiation and relative strength. The signals received by the microphones are processed to reveal the sound source location and are usually mapped on a planar surface. Because the

distance from each source to each microphone in the array varies, all the signals will have a relative time delay. The pressure can be computed at any point in front of the array, taking into account the time delay corresponding to the propagation distance. Because the original sound signal is estimated by adding time delay and summing the signals, this method is called "Delay and Sum" beamforming which is performed in the time domain. There are several methods also performed in the frequency domain but are closely related to the time domain methods.

[0014] Known in the art is Sijtsma, P., "Experimental techniques for identification and characterization of noise sources", National Aerospace Laboratory, NLR-TP-2004-165, April 6, 2004, which is said to provide an introduction of phased array beamforming with microphone arrays. Beamforming is considered both in the time-domain and in the frequency-domain. Conventional beamforming techniques are treated, but also more advanced techniques. Special attention is paid to the localization of moving sources. Applications are shown of wind tunnel measurements and aircraft fly-over measurements.

[0015] Also known in the prior art is Ulf Michel "History Of Acoustic Beamforming," Berlin Beamforming Conference (BeBeC), Berlin, Germany, November 2006, which is said to review the development of the beamforming method (also called microphone antenna, phased array of microphones, acoustic telescope, or acoustic camera). The microphone antenna was invented by Billingsley (1974) and has since seen dramatic improvements due to the availability of better data acquisition and computing hardware. Recent mathematical and software developments invert the beamforming process and allow a quantitative determination of the sources. Beamforming is indispensable for the localization of sound sources on moving objects, on flying aircraft, on high-speed trains, on motor cars in motion, on open rotors like helicopter and wind turbine rotors. In these applications, the ability to follow the motion of the sources is important. The second important applications are source localization tests in the test sections of open and closed wind tunnels. The background noise suppression capability of the beamforming method is required here. The various applications are discussed with a long list of references.

[0016] Also known in the prior art is Stefan Oerlemans, "Detection of aeroacoustic sound sources on aircraft and wind turbines," Ph.D. Thesis, University of Twente, The Netherlands, September 4, 2009, which is said to disclose the detection of aeroacoustic sound sources on aircraft and wind turbines using phased microphone arrays. The characteristics of

flow-induced sound from aircraft wings and wind turbine blades are derived and summarized. The phased array technique is described in detail, and several aspects of the method are discussed, for example how to account for the effects of flow and moving sources, and how to quantify array results using a source power integration method.

[0017] There is a need to provide improved low-cost monitoring of components and coordinated sensing on wind farms.

SUMMARY OF THE INVENTION

[0018] According to one aspect, the invention features a damage or defect detection system. The system comprises a hollow mechanical structure having a closed shell, the shell dividing space into an interior volume of the structure and an exterior volume outside the hollow mechanical structure; at least one of: (a) a first sound receiver situated within the interior volume of the hollow mechanical structure, the first sound receiver configured to receive sounds generated by the relative motion of the hollow structure and the surrounding air and to generate first electrical signals representative of the sounds; and (b) a second sound receiver situated in the exterior volume outside the hollow mechanical structure and a sound generator situated within the interior volume of the hollow mechanical structure, the first sound receiver configured to receive sounds generated by the sound generator situated within the interior volume of the hollow mechanical structure and to generate second electrical signals representative of the sounds, the sound generator configured to generate sound in response to third electrical signals received by the sound generator; a wireless transmitter configured to receive the first electrical signals from the first sound receiver, the second electrical signals from the second sound receiver and configured to communicate the signals to a data processing system, and configured to receive driving signals from the data processing system and to communicate the driving signals to the sound generator as the third electrical signals; the data processing system configured to analyze the first and the second electrical signals to determine a result that describes whether damage or a defect is present in the closed shell of the hollow mechanical structure and configured to perform at least one of displaying the result to a user, recording the result, and transmitting the result to another system for further processing.

[0019] In one embodiment, the hollow mechanical structure having a closed shell is a blade of a wind turbine.

- [0020] In another embodiment, the damage is one or more of a hole, edge split or a crack.
- [0021] In yet another embodiment, the sound generator is configured to generate sound in the range of frequencies from 50 Hz to 20 KHz.
- [0022] In still another embodiment, the sound generator is configured to generate sound in the range of frequencies from 500 Hz to 10 KHz.
- [0023] In a further embodiment, the sound generator is configured to generate sound in the range of frequencies from 1 KHz to 5 KHz.
- [0024] In yet a further embodiment, the sound generator is configured to generate sound in the ultrasonic frequency range.
- [0025] In an additional embodiment, the wireless transmitter is configured to operate according to an IEEE protocol for wireless transmission.
- [0026] In one more embodiment, the wireless transmitter and the data processing system are configured to communicate using the Internet.
- [0027] In still a further embodiment, the data processing system is a cloud-based data processing system.
- [0028] In one embodiment, the data processing system comprises a general purpose programmable computer that operates under the control of instructions recorded on a machine readable medium.
- [0029] According to another aspect, the invention relates to a defect detection method. The method comprises the steps of: providing a damage or defect detection system, comprising: a hollow mechanical structure having a closed shell, the shell dividing space into an interior volume of the structure and an exterior volume outside the hollow mechanical structure; at least one of: (a) a first sound receiver situated within the interior volume of the hollow mechanical structure, the first sound receiver configured to receive sounds generated by the relative motion of the hollow structure and the surrounding air and to generate first electrical signals representative of the sounds; and (b) a second sound receiver situated in the exterior volume outside the hollow mechanical structure and a sound generator situated within the interior volume of the hollow mechanical structure, the first sound receiver configured to receive sounds generated by the sound generator situated within the interior volume of the hollow mechanical structure and to generate second electrical signals representative of the

sounds, the sound generator configured to generate sound in response to third electrical signals received by the sound generator; a wireless transmitter configured to receive the first electrical signals from the first sound receiver, the second electrical signals from the second sound receiver and configured to communicate the signals to a data processing system, and configured to receive driving signals from the data processing system and to communicate the driving signals to the sound generator as the third electrical signals; the data processing system configured to analyze the first and the second electrical signals to determine a result that describes whether a defect is present in the closed shell of the hollow mechanical structure and configured to perform at least one of displaying the result to a user, recording the result, and transmitting the result to another system for further processing; in the event that the apparatus described in paragraph (a) above is present, performing the steps of: receiving first electrical signals at the wireless transmitter; communicating the first electrical signals to the data processing system; and analyzing the first electrical signals to determine a result that describes whether a defect is present in the closed shell of the hollow mechanical structure; in the event that the apparatus described in paragraph (b) above is present, performing the steps of: providing driving signals to the sound generator as the third electrical signals to operate the sound generator; receiving second electrical signals at the wireless transmitter; communicating the second electrical signals to the data processing system; and analyzing the second electrical signals to determine a result that describes whether a defect is present in the closed shell of the hollow mechanical structure; and whichever of the apparatus in paragraph (a) or paragraph (b) is present, performing at least one of displaying the result to a user, recording the result, and transmitting the result to another system for further processing.

[0030] The foregoing and other objects, aspects, features, and advantages of the invention will become more apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] The objects and features of the invention can be better understood with reference to the drawings described below, and the claims. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the drawings, like numerals are used to indicate like parts throughout the various views.

- [0032] FIG. 1A is a bar graph that indicates that problems with rotor blades occur at about a 20% rate per year and involve downtime of several days per incident, on average.
- [0033] FIG. 1B is a cutaway view of a wind turbine system.
- [0034] FIG. 1C is an image of damage to roller bearings in a wind turbine system.
- [0035] FIG. 1D is an image of damage to gears in a wind turbine system.
- [0036] FIG. 1E is an image of a generator in a wind turbine system.
- [0037] FIG. 1F is an image of a field-deployed wind turbine and crane for servicing.
- [0038] FIG. 1G is an image of a fire in a wind turbine.
- [0039] FIG. 1H is an image of damaged rotor blades in a wind turbine.
- [0040] FIG. 2A is an image of leading edge damage to a rotor blade of a wind turbine.
- [0041] FIG. 2B is an image of trailing edge damage to a rotor blade of a wind turbine.
- [0042] FIG. 2C is an image of a damaged rotor blade that is missing a portion thereof.
- [0043] FIG. 2D is an image of a damaged rotor blade.
- [0044] FIG. 2E is an image of damage at a tip of a rotor blade.
- [0045] FIG. 2F is an image of damage to a rotor blade.
- [0046] FIG. 2G is an image of filamentary material (e.g., thread, twine, yarn, rope, wire or the like) used for sensing of damage in rotor blades.
- [0047] FIG. 3A through FIG. 3D illustrate an example of beamforming performed on a 52 m diameter, 65 m high, Gamesa wind turbine during operation.
- [0048] FIG. 4 is a schematic diagram illustrating the systems and methods of the invention for damage detection and identification applied to a typical utility-scale operating wind turbine.
- [0049] FIG. 5A is a schematic diagram in cross section of a wind turbine blade section having microphones used to detect damage from the airflow excited acoustic signature.
- [0050] FIG. 5B is a schematic diagram in cross section of a wind turbine blade section having a microphone external to the turbine used to detect blade damage from an internal speaker ensonifying the internal cavity.
- [0051] FIG. 5C is a diagram of a cross section of a typical wind turbine blade with audio speakers ensonifying the internal cavities according to principles of the invention. Defects and damage reveal themselves as changes to the external sound radiation pattern.

[0052] FIG. 6 is a schematic diagram of the sensor and the sensor fusion base node apparatus and instructions recoded on a machine-readable medium (also called “software”), as well as images of the sensor and base node apparatus (also called “hardware”).

[0053] FIG. 7 is a schematic diagram showing the locations and the interactions among the rotor blades, the sensor, the sensor fusion base node, the wind turbine equipment housed in the wind turbine nacelle, a wireless communication system, a user, a data processing system and a monitoring location.

[0054] FIG. 8A is an image of a circular microphone array.

[0055] FIG. 8B is an image of a circular microphone array with a composite box having various deliberately added defects, positioned so as to make measurements according to principles of the invention.

[0056] FIG. 8C is an image of the acoustic beamforming measurement result, superimposed on the image of the box with and internal speaker, illustrating that the ensonification method reveals the location of the 1mm, 3mm, and 5mm diameter holes and the line crack.

[0057] FIG. 9A is an image of the deliberately damaged side of the box, showing the 1mm, 3mm, and 5mm diameter holes and the line crack.

[0058] FIG. 9 is an image showing the location and geometry of the damaged face of the box.

[0059] FIG. 9C is an image showing the inside of the box.

[0060] FIG. 9D is a view of a test setup showing the distances between the box and a microphone, and the distance between the box and an external blower used to generate noise.

[0061] FIG. 10A is an image of the ring microphone array in the foreground with a wind turbine blade section in the background.

[0062] FIG. 10B is an image showing a section of the blade and a superimposed acoustic map of the sound radiated from the blade with holes in the blade.

[0063] FIG. 10C is an image in close-up of the three holes (1, 3, and 5 mm diameter) that are detected by the ring array.

[0064] FIG. 11A is a graph that illustrates the influence of prescribed damage on the sound pressure inside the cavity excited both by the audio speaker and the air blower.

[0065] FIG. 11B is a graph that illustrates the influence of prescribed damage on the sound pressure outside the cavity excited by the audio speaker only.

[0066] FIG. 12A is a perspective view of a finite element 2D mesh applied to the surface of a solid model of the box with a virtual audio speaker ensonifying the internal cavity,

[0067] FIG. 12B is a perspective view of a sound pressure distribution on a virtual surface right outside the box and at the proximity of the damaged side,

[0068] FIG. 12C is a perspective view of the superimposed mesh, pressure distribution and damage locations.

DETAILED DESCRIPTION

[0069] As used herein, the term “passive system” (or the word “passive” used in conjunction with acoustic noise generation systems) is understood to refer to a system that relies upon noises generated when natural wind, the noise caused by the relative motion of the turbine blades through the air when the turbine is operating, or a similar external source of energy excites turbine blades.

[0070] As used herein, the term “active system” (or the word “active” used in conjunction with acoustic noise generation systems) is understood to refer to a system that relies upon noises generated by a specific sound source or sound generator such as an audio speaker, an ultrasonic sound source, or a similar source that relies upon sound waves that are deliberately generated.

[0071] We are not aware of any prior technologies that can measure leading and trailing edge cracks or holes on a rotating turbine blade. Placing multiple sensors on the rotating blades involves complicated mechanical interconnections due to the wiring, such as requiring slip-rings for power and data transmission, and involves installation difficulties.

[0072] The present invention is a fundamental departure from existing structural health monitoring (SHM) approaches as it makes operational damage detection and identification (severity, location, and type of damage) of cavity structures (i.e. turbine blades) possible. Modern wind turbine blades consist of composite airfoil shaped structures that form a hollow acoustic cavity. Because of continually varying aerodynamic forces, gravitational loads, lightning strikes, and weather conditions, all blades can be expected to experience leading and

trailing edge splits, cracks, or holes that are currently not detectable except by visual inspection or post blade failure.

[0073] The innovative techniques utilize (1) low-cost, low-maintenance microphones for passive monitoring of natural aerodynamically-driven, flow-induced noise that couples with the structural damage and (2) acoustic sources (with internal and external microphones) to excite the dynamic cavity structure from within. The blade damage manifests itself in changes to the acoustic cavity frequency response functions and to the blade acoustic transmission loss. A plurality of wireless microphones can be used for the cavity-internal passive detection and a single microphone or an array located outside but nearby the cavity structure can be used for the cavity-external active detection of damage.

[0074] We have demonstrated two new approaches for detecting defects in wind turbine blade structures. The first one is the passive detection approach that leverages the energy caused by the flow-induced noise due to wind, exterior to the cavity. This approach is inexpensive, in-situ, and is effective to detect holes, cracks and leading/trailing edge splits in bonded surfaces. In operation, the cavity of the structure (turbine blade) can be continuously monitored and when damage is originated, the internal acoustic signature will change due to the changes in the transmission loss (caused by the hole or crack) of the composite material and/or the distorted acoustic pressure field. The sound field inside the blade will be significantly different when the blade cavity is no longer sealed to the fluid passing over the exterior of the blade (see for example FIG. 5A). A single acoustic sensor (such as a microphone) inside the blade cavity can be used to track the differential noise component caused by the damage (i.e. cracks and holes) which essentially couples the blade cavity to the exterior airflow. This is analogous to a Helmholtz resonator similar to the noise generated by the airflow over a glass bottle or a musical reed. Another everyday example of this effect is experienced when a window of a traveling automobile is cracked open ever so slightly and the resulting noise inside the cabin changes significantly due to the energy of the exterior aerodynamic flow entering the cabin. Structural damage will manifest itself as noise (the aerodynamic energy) that is transmitted through the composite blade structure and will cause significant changes to the internal cavity acoustics.

[0075] The second approach is called the active detection approach, and involves mounting an audio source such as a speaker inside of the cavity structure to excite the internal

cavity acoustics. It is possible to detect cracks or damage within the structure by observing the deterministically controlled sound radiation from the cavity (see FIG. 5B). The audio speaker driving frequency is controllable to ensure acoustic radiation levels and spectral content can be discriminated from the turbine aerodynamic and background noise while being correlated to the structural damage. The damage will present itself as detectable features when observed by a single microphone external to the cavity (turbine blade). A modern utility-scale wind turbine blade is a completely enclosed cavity. When a crack, leading or trailing edge split, or hole is developed in the structure, the acoustic energy (controllable and deterministic) from the speaker will be transmitted outside of the composite blade structure. A single microphone sensor or an array of microphones located outside the cavity can be used for health monitoring and damage detection purposes.

[0076] The primary risks for implementing a single microphone or a beamforming array damage detection approach include the possibility that the techniques are insensitive to some types of damage, possibility that the spatial resolution will be too coarse to measure at a distance, and possibility that flow-induced noise masks the deterministic noise source thereby interfering with the detection or quantification of the defects. These risk factors have been mitigated by utilizing different microphone array sequencing, beamforming weighting patterns (e.g. Dolph-Chebyshev) and changing the deterministic source characteristics to have a spectral content that is uncorrelated with the aerodynamic flow noise, enabling detection.

[0077] On an operational full-scale wind turbine, the cavity-internal passive detection can be conducted by using one microphone per blade cavity as shown in FIG. 4. In case there is more than one uncoupled cavity in a blade (some blades are partitioned into two compartments by a rigid shear web), each cavity will carry one wireless microphone (see FIG. 5A). Similarly, each cavity can be assigned a wired or wireless audio speaker that will generate random broadband noise with a different mean frequency and standard deviation. The source strengths and frequency bandwidth of the audio speakers will be controllable and chosen to differ from the aerodynamic and turbine background noise determined from the results of the computational and empirical investigations of the flow-induced noise content. In this way, the damaged blade will be distinguishable from other noise sources when received by the reference microphone located right underneath the nacelle. Moreover, a smart sequential blade timing algorithm for each blade can be introduced based upon this reference microphone

signal and its cross correlation with the cavity-internal microphone signals. This information can be used in conjunction with the acoustic signals to demodulate the audio signal received by the reference microphone to identify which blade is damaged. From acoustic Doppler shifts and knowing rotation rate it will be possible to determine the approximate location of damage on the blade from the spectral content because the blade speed (e.g., the velocity of rotation of a point on the blade) varies linearly from the root to the tip of the blade. For the cavity-internal sensors, a hybrid signal processing strategy with a smart blend of time, frequency and time-frequency domain analysis capability can be fused. Time domain acoustic signals can be used for damage surveillance through the use of condition indicators. A time trend analysis can continuously monitor if the changes to the signals are consistent to assist in detection of the damage versus false alarms. Time signals can be converted into the frequency domain by using the fast Fourier transform (FFT) at discrete time intervals (every few seconds, minutes, hours, days, or longer) and spectral kurtosis (indicator of peakiness) can be monitored to detect for any changes to the baseline frequency spectrum. When both time and frequency domain results indicate a consistent change in the signal content, then a continuous wavelet transform based time-frequency analysis can be executed by sampling the time domain signals at a much faster rate than the regular sampling rates used. For the cavity external reference sensor signal, the Hilbert transform based demodulation of the acoustic signal can be exploited. Trend analysis can be carried out on the cross correlation of the cavity-external signal and each of the cavity-internal signals and results can be monitored for damage detection. The acoustic interrogation could take place essentially continuously in time periods as short as fractions of a second, or periodically at intervals, such as hourly, daily, weekly, or longer. Because the acoustic excitation frequencies are controlled and are very different from the nominal turbine aerodynamic noise, it is expected that holes and leading/trailing edge splits will be readily identified at a much earlier stage of deterioration, thus facilitating a scheduled, smaller scale blade repair. The prescribed single reference microphone located exterior to a turbine can be used to simultaneously detect damage on all three turbine blades and once damage is detected, a beamforming array can be used to accurately locate damage on a specific blade. The acoustic source strength and frequency content for the cavity internal deterministic sound sources can be made distinguishable from dominant stochastic flow-induced (wind) noise. The sound to be generated by the internal audio speakers will be detectable under the effect of stochastic flow-

induced (aerodynamic) noise. A analytical or numerical model of the cavity acoustics will be able to help identify the damage type and severity level from the acoustic leakage.

[0078] Improvements in reliability and energy capture can be achieved by implementing a wireless (or wired) sensor network that will monitor structural health, detect failures or damage, and help predict when failure will occur. Improvements in mechanical reliability can be made by a wireless sensor network that periodically interrogates structural health and transmits data to a sensor fusion system. An inexpensive wireless sensor network would therefore be able to perform total structural health monitoring of the blades, reducing the economic impact of schedule-based maintenance and decreasing the likelihood of structural catastrophic failure. Data extracted from the various monitoring sensors on the turbine blades will be stored by using cloud and connected devices. Wind farm owner/operators can remotely interrogate the condition and integrity of their wind turbine blades by using wireless cellular services.

[0079] A well-balanced mix of simple/traditional and advanced signal processing approaches can be employed for fault detection within the nacelle and turbine blades. Multi-domain signal processing techniques such as Hilbert-Huang Transforms and Wavelet transforms can be implemented to reveal time-varying signals due to defects by exploiting peaks both in time and frequency domains simultaneously. It is expected that the system will detect damage to blades. Audio speakers can also be used inside the blade to observe changes in the acoustic signature external to the blade. When cracks, holes, or damage are present the audio signals will become apparent to microphones placed near the base of the turbine.

[0080] The sound frequencies that are effective for use in the systems and methods of the invention are preferably in the range of 1 KHz to 5 KHz, but it is expected that sound in the ranges of 50 Hz to 20 KHz, 500 Hz to 10 KHz, and possibly ultrasonic frequency ranges can be effectively employed.

[0081] FIG. 4 is a schematic diagram 400 illustrating the systems and methods of the invention for damage detection and identification applied to a typical utility-scale operating wind turbine. In FIG. 4, there is illustrated a wind turbine having a support pillar 405, a plurality of blades 410, sound sources 420 (such as loudspeakers LS 1, LS2 and LS3) located inside each blade 410, sound receivers 430 located inside each blade (such as microphones mic1, mic2 and mic3), and a reference sound receiver 435 located within or on the wind

turbine structure (such as a reference microphone ref mic). Also illustrated in FIG. 4 are defects (generally 440) such as holes 440', cracks 440'' and edge splits 440 '''. A wind flow 450 external to the wind turbine is illustrated as well. The wind flow 450 is a natural phenomenon in which the wind direction and the velocity are variable with time, in addition to the relative motion of the turbine blades relative to a fixed position, such as the support tower 405 of the wind turbine. As will be explained in more detail, the system shown in FIG. 4 can operate either as a passive system in which acoustic noise is generated by the wind flow.

[0082] We describe a system to detect cracks in wind turbine blades (rotor blades) and other structures using wireless sensors and active noise generation systems. For blades the system uses conductive fibers that are embedded or attached to near the leading and trailing edge or other areas, such as a spar cap, that are prone to cracking.

[0083] The system interrogates the condition of the rotor blade inexpensively by using wireless sensor nodes and conductive fiber. In various embodiments the conductive fiber may be embedded or attached to the rotor blade.

[0084] The inventors are not aware of any other structural health monitoring (SHM) systems that can detect cracks over a large area on a turbine blade.

[0085] A unique feature of the design is the integration of the system with the sensors in the nacelle that can measure acceleration, sound (for example, using a microphone), temperature, strain, and other parameters on components such as the generator, gearbox, rotor, main bearing, and other components in modern wind turbines.

[0086] In various embodiments, the systems and methods of the invention can be applied to both existing turbines and new turbines throughout the wind energy industry.

[0087] The wind turbine structural health monitoring system is expected to allow operators to observe and monitor the current health status of a wind turbine in real-time. As a result, the expected need for repairs can be better anticipated, and repair services can be efficiently and quickly scheduled.

[0088] This invention improves the existing state of monitoring in wind turbines to help drive down the cost of energy. Improvements in reliability and energy capture are expected to be achieved by implementing a wireless sensor network that allows optimization of turbine energy generation efficiency while providing a prognosis of when component failure will occur. Improvements in reliability of mechanical components, such as in blades, are

expected to be made by a wireless sensor network that periodically interrogates structural health and transmits data to a sensor fusion system. An inexpensive wireless sensor network would therefore be able to perform total turbine blade structural health monitoring, reducing the economic impact of schedule-based maintenance and decreasing the likelihood of structural catastrophic failure. It is expected that the wind turbine structural monitoring system will rely heavily on a commercial wireless network, for example a network provided by a commercial telephone company, an internet service provider, or a dedicated wireless network. Data extracted from the various monitoring sensors on the turbines and wind farms will be stored by using cloud and connected device services. Wind farm owner/operators are expected to remotely interrogate the condition and integrity of their wind turbine components by using such wireless capabilities. In one embodiment, the system is expected to incorporate a number of wireless/wireline services, connected device services, and cloud services.

[0089] The microphone sensors can be placed within each blade connected using wires or using a wireless system. The microphones (internal and external to the blades) can be used to detect changes in the acoustic signature of the blade to reveal damage (leading and trailing edge splits, or holes and cracks in the turbine blade). The sensors inside and outside the cavity structure will be able to measure the differences between the content of operational noise (both stochastic and deterministic) and the damage induced acoustic perturbations. Advanced signal processing algorithms based upon a well-balanced fusion of time, frequency and time-frequency domain methods can be implemented to detect damage. Time trending and associated statistical condition indicators can be employed to differentiate defects and damage from operational effects and natural operating changes to the system. The acoustical transfer functions of the cavity can be used to detect the influence of different damage types and severity levels on the resultant acoustic radiation. Once damage is detected, acoustic beamforming (with a microphone array) can be used to help quantify the precise location of damage by observing the acoustic transmission loss and radiation of the composite material as a function damage types and severity (see for example FIG. 4).

DESCRIPTION OF VARIOUS EMBODIMENTS

[0090] FIG. 5A is a schematic diagram in cross section of a wind turbine blade section 500 having microphones 510 used to detect damage from the airflow excited acoustic

signature. The wind turbine blade is a hollow mechanical structure having a closed shell, the shell dividing space into an interior volume of the structure and an exterior volume outside the hollow mechanical structure. While the present invention is described as being useful in a preferred embodiment for detecting damage to, or flaws in, wind turbine blades, it is expected that it can also be used to detect damage or flaws in other structures that comprise a hollow mechanical structure having a closed shell.

[0091] FIG. 5B is a schematic diagram in cross section of a wind turbine blade section 500 having a microphone 545 external to the turbine used to detect blade damage from one or more internal speakers 540 ensonifying the internal cavity.

[0092] In FIG. 5A and FIG. 5B the cross sectional view of a turbine blade 500 has defects including holes and cracks 520, a leading edge split 522 and a trailing edge split 524. From a comparison of FIG. 5A with FIG. 5B, one sees that in various embodiments it is possible to have the components shown and described for FIG. 5A that operate as a passive system, the components shown and described for FIG. 5B that operate as an active system, or both sets of components present in a single wind turbine. The passive system and the active system are not mutually exclusive, and in some instances can be used sequentially or together.

[0093] FIG. 5C is a diagram of a cross section of a typical wind turbine blade with audio speakers ensonifying the internal cavities according to principles of the invention. Defects and damage reveal themselves as changes to the external sound radiation pattern. By mounting an audio speaker inside of the wind turbine blade, it is possible to detect cracks or damage within the structure by observing the sound radiated from the blade.

[0094] FIG. 6 is a schematic diagram of the sensor and the sensor fusion base node apparatus and instructions recoded on a machine-readable medium (also called “software”), as well as images of the sensor and base node apparatus (also called “hardware”). As illustrated in FIG. 6, a wireless sensor node 610 (for example a ZigBee wireless sensor node) receives signals from one or more sound receivers such as microphone 510 or microphone 545, and processes the received signals according to a wireless mode protocol. The wireless sensor node 610 transmits the signals according to a protocol such as IEEE 802.15.4 (or in some instances 802.15.4 (ZigBee)). ZigBee is a specification for a suite of high-level communication protocols used to create personal area networks built from small, low-power digital radios. ZigBee is based on an IEEE 802.15 standard.

[0095] The Sensor fusion base node 620 receives the transmitted signals from the wireless sensor node 610 and processes the signals so that they can be analyzed, and further transmitted, displayed to a user, or stored, as may be convenient or desired.

[0096] The base node 620 serves as the hub of the sensor network to transmit sensor data to data analysis instruments located in a cloud computing infrastructure. The base node 620 has both a sensor node and a data modem attached. The sensor data are relayed to the base node through the sensor data network. In some embodiments, the data communication from the base node to the data analysis instrument is carried out via a wired network or a 3G/4G/LTE data network.

[0097] FIG. 7 is a schematic diagram showing the locations and the interactions among the rotor blades, the sensor, the sensor fusion base node, the wind turbine equipment housed in the wind turbine nacelle, a wireless communication system, a user, a data processing system and a monitoring location. While the sensors in FIG. 7 are described as crack sensors, they can equally well be sound sensors such as one or more microphones situated within the hollow interior of the wind turbine blade.

Wireless/Wireline Services

[0098] Sensor data collected from the system are transported to the Internet using a wireless/wireless service, such as Verizon's wireless/wireless services. In view of the possibility that large volumes of sensor data may be collected, a high-speed network with adequate capacity is advantageous. Networks of commercial vendors such as are provided by Verizon is helpful for the smooth operation and success of the system.

Wireless Sensor Network

[0099] In one embodiment, a suite of sensors are placed on wind turbines to measure the turbine components. In one embodiment, these sensors are connected via wireless links such as Zigbee for coordination, routing, control, and other network functionalities. In one embodiment, the sensor data are aggregated to a smart device (e.g., a smart phone or customized device) connected to Verizon's high-speed data networks.

Connected Device Services

[00100] A growing number of devices have been connected to the Internet via wireless networks for monitoring and control of the physical world. Commercial vendors such as Verizon now provide a range of connected device services that help businesses to connect to and manage their smart devices used in asset shipping/tracking, health care, vehicle operation monitoring, vending machines and other commercial applications. Utilizing the connected device service capability in the wind energy business will have great economic, societal, and environmental impacts on a global scale. One advantage is that a deployed system can be monitored remotely from any convenient location that has a connection to the Internet, including the possibility of having monitoring provided by a plurality of locations distributed across time zones such that the 24 hour day is divided into 3 or more time segments, each corresponding to the normal business hours in the location where the monitoring takes place. This allows for convenient full time monitoring, and for convenient “hand-off” of monitoring from one monitoring station to the next with little or no inconvenience to any operator at any monitoring station.

Cloud Services

[00101] In some embodiments, sensor data is expected to be transported over a cloud service (e.g., a remote Internet-based storage and computation service) for reliable, secure storage, and further data analysis. In some embodiments, the cloud service is Verizon’s Cloud service. It is expected that in some embodiments, a cloud-based web service can be used with the wind turbine monitoring system. A visual user interface includes support for worldwide mapping, charting of sensor data, establishment of alerts, dispense of maintenance and repair services, and other device management.

Data Transport to the Cloud

[00102] In one embodiment, collected sensor data is transported from the smart devices through Verizon’s high speed wireless data networks to its cloud services for data storage and further data analysis and management.

Cloud-based Asset Monitoring and Management

[00103] In one embodiment, a web service is provided for use with the wind turbine monitoring system. The visual user interface includes support for worldwide mapping, charting of sensor data, establishment of alerts, dispatching of maintenance and repair services, and device management.

ALTERNATIVE EMBODIMENT OF SENSORS

[00104] The crack sensors can be made from a thin conductive fiber (commercially available from Liberator, coated Vectran, Shieldex, EY Technologies) that is embedded or attached to the inner or outer surface of the blade, near the leading or trailing edge, or the spars/shear webs, and spar caps. The crack sensors can also be fabricated from conductive ink that is painted on using a brush, pen, or screen. When a crack is developed, the fiber or conductive pathway will break revealing damage in a specified location. The Sensor nodes allow for multiple crack sensors distributed over the entire turbine blade. Additionally the crack sensors can be daisy-chained together to reduce the amount of conduct fiber used. Therefore instead of having a single node acting independently, a multiple number of nodes can be coupled together to detect cracks in a spatially distributed manner.

[00105] Crack sensor data and acoustic data are relayed to a base node through a wireless network for data fusion and further analysis. A low power sensor node connects to and manages crack sensors and a microphone, and has wireless communication capabilities such as Zigbee protocol. The sensor node is activated periodically to read crack sensor status and perform analog to digital conversion on microphone voltage. The digitized data are transmitted to other sensor nodes for relaying, or directly to the base node if distance and shielding conditions permit. The duty cycle of the sensor node may be very short such as one minute per day to save power, because the sensor data (crack and acoustic) do not have inherent real-time requirements. In other embodiments, the system can be interrogated continually. The operation of the sensor node is controlled by its firmware, which is generated through a software development procedure. The sensor nodes have the option to interconnect with wires if wireless communication is obstructed or interfered.

REDUCTION TO PRACTICE

[00106] FIG. 8A is an image of a circular microphone array 810.

[00107] FIG. 8B is an image of a circular microphone array with a composite box 820 having various deliberately added defects, such as crack 840, positioned so as to make measurements according to principles of the invention.

[00108] FIG. 8C is an image of the acoustic beamforming measurement result, superimposed on the image of the box, illustrating that the method reveals the location of the 1mm, 3mm, and 5mm diameter holes and the line crack 840.

[00109] We used a ring array 810 that had 48 microphones, as shown in FIG. 8A, to measure the sound radiation of a composite box and a section of a wind turbine blade, both of which had an audio speaker placed inside. The results on the composite box clearly reveal that the beamforming technique can identify the line crack 840 and three holes with different diameters as shown in FIG. 8C.

[00110] Tests were conducted to verify that the sound transmitted through the composite box with the damaged panel could be detected by using a ring-microphone acoustic beamforming array (from Polytec). Additional tests were conducted using a wind turbine blade section (3 m long). Both the box and the wind turbine blade section contained an audio speaker used to generate sound within the cavity. When the panels and blade were undamaged, no sound was detectable. When the box's panel and the turbine blade were damaged, the array was clearly able to detect the location of the damage emanating from the cavity structures as shown in FIG. 8 and FIG. 9.

[00111] FIG. 9A is an image of the deliberately damaged side of the box, showing the 1mm, 3mm, and 5mm diameter holes and the line crack.

[00112] FIG. 9 is an image showing the location and geometry of the damaged face of the box.

[00113] FIG. 9C is an image showing the inside of the box.

[00114] FIG. 9D is a view of a test setup showing the distances between the box and a microphone, and the distance between the box and an external blower used to generate noise.

[00115] Two microphones and an air blower were used to simulate the test conditions. One of the walls of the composite box contained prescribed damage (3 holes with diameters of 1 mm, 3mm and 5mm, and a diagonally oriented crack approximately 3 mm thick) as shown in FIG. 9A. The composite box (cube with 35 cm edges) was positioned with the damaged panel pointing toward the outside measurement microphone while another microphone was located

inside the cavity along with a low-cost audio speaker (see FIG. 9B and FIG. 9C). The audio speaker was used to generate a narrow band excitation signal from inside the cavity that was used for active damage detection. The internal microphone was used to detect sound pressure variations for the case when the panel had the damage compared to the undamaged case.

[00116] The external microphone was positioned 1.5 m away from the panel with prescribed damage. An air blower located approximately 1.8 m away from the box was used to generate flow-induced noise to artificially contaminate the content of the sound received by both the internal and the external microphones (see FIG. 9D). These tests were conducted in four sequential steps, while the cavity internal audio speaker and both microphones were kept operational throughout. The composite box was first tested with an undamaged panel, later with the damaged panel while air the blower was not operating, and finally with the blower turned on to mimic the wind flow generated noise. The sound pressure was recorded using both microphones for 15 seconds for each test and the spectra obtained were used to help justify the hypothesis. Even though the sound sources used were not optimized for this experiment, comparison between the damaged and undamaged cases clearly exhibits the influence of flow-induced noise from the air blower on the overall spectrum, which is described further with regard to FIG. 11A. The data reveals that the sound outside the enclosure attributed to the audio speaker inside the box was easily detected when air blower was not operational, which is described further with regard to FIG. 11B. In the embodiments that were investigated, data captured by the microphone outside also clearly revealed the sound radiated by the loudspeaker inside the cavity, even under the influence of the nearby operating blower.

[00117] FIG. 10A is an image of the ring microphone array 810 in the foreground with a 3-m section of a composite wind turbine blade 1010 in the background.

[00118] FIG. 10B is an image showing a section of the blade and a superimposed acoustic map of the sound radiated from the blade with holes in the blade.

[00119] FIG. 10C is an image in close-up of the three holes 1001, 1003, 1005 having respectively 1 mm diameter, 3 mm diameter and 5 mm diameter that are detected by the ring array.

[00120] FIG. 11A is a graph that illustrates the influence of prescribed damage on the sound pressure inside the cavity excited both by the audio speaker and the air blower.

[00121] FIG. 11B is a graph that illustrates the influence of prescribed damage on the sound pressure outside the cavity excited by the audio speaker only.

COMPUTATIONAL INVESTIGATION OF ACOUSTIC RADIATION FROM A DELIBERATELY DAMAGED CAVITY STRUCTURE

[00122] FIG. 12A is a perspective view of a finite element 2D mesh applied to the surface of a solid model of the box with a virtual audio speaker ensonifying the internal cavity,

[00123] FIG. 12B is a perspective view of a sound pressure distribution on a virtual surface right outside the box and at the proximity of the damaged side,

[00124] FIG. 12C is a perspective view of the superimposed mesh, pressure distribution and damage locations.

[00125] The box with a damaged panel previously described was additionally modeled using the boundary element model to simulate the acoustic radiation emanating from the composite box with an internal audio speaker. The predicted sound pressure distribution outside the panel with the damage was determined to be in agreement with the patterns measured in the preliminary beamforming tests, as is shown in FIG. 12. The geometric model of the box was created in Solidworks and meshed using Abaqus. The meshed model was imported into the boundary element model (Coustyx) and the acoustic equations were solved for simulating the pressure distribution when a virtual sound source (a monopole generating a pure tone at 1 kHz) was placed at the mid-point on the bottom of the box. For the preliminary simulations, flow-induced effects were excluded for simplicity and the sound pressure maps were generated using a virtual microphone array including 64 (8 x 8) equally-spaced microphones located 1 mm away from outer damaged panel.

DETECTION OF OTHER MECHANICAL DEFECTS

[00126] A well-balanced mix of simple/traditional and advanced signal processing approaches is expected to be employed for fault detection within the nacelle and turbine blades. A special technique that resolves the added complexity due to complicated planetary gear design, kinematics and time-varying vibration signal transmission paths is expected to be implemented to improve detection of planetary gear faults. A Hilbert Transform-based adaptive amplitude and phase demodulation method is expected to be used to detect the gear

defect signals that couple to the blade cavity acoustics and radiated sound. This methodology uses time-synchronous-averaging to isolate the periodic signals. Multi-domain signal processing techniques such as Hilbert-Huang Transforms and Wavelet transforms is expected to be implemented to reveal time-varying signals due to defects by exploiting peaks both in time and frequency domains simultaneously. It is expected that the system is expected to detect tooth breakage, pitting, loose parts, and scuffing wear in addition to the demonstrated detection of damage to blades.

ADVANTAGES PROVIDED BY THE INVENTION

[00127] Among the numerous advantages that one can expect the invention to provide are at least the following:

[00128] The detection of defects such as holes and cracks, which in general are created by random and unpredictable events such as lightning strikes or objects hitting a blade allows the rapid and convenient determination that the affected wind turbine needs to be repaired. This allows the operator to secure the wind turbine in good time, before further damage may occur, and to make repairs in a timely and efficient manner.

[00129] The detection of damage cause by wear can be used in the same manner as has just been described, but can also be used to build a database of operational characteristics of individual wind turbines or of models or classes of wind turbines, so that scheduled maintenance can be performed, rather than being obliged to take a wind turbine out of operation for unscheduled maintenance. This ability to plan can lead to better efficiency in wind turbine operation and power generation. For example, a power into grid has to be balanced across turbines, and being able to plan outages in advance can help in maintaining such balance.

[00130] It is expected that the data about operation condition of wind turbines can be used to improve designs and methods and/or materials of construction. The data can be used to diagnose failure modes and frequencies of various wind turbine models and designs, which is expected to lead to improvements in wind turbine blade construction and operational characteristics.

[00131] Rapid diagnosis of the presence of a small defect can also lead to improvements in making necessary repairs which will have the effect of mitigating liability issues that might

arise from subsequent damage to the wind turbine, and avoid potential liability issues that might arise from accidents or from out-of-operation conditions caused by more serious damage to the wind turbine if repairs are put off because the small defect went unnoticed.

DEFINITIONS

[00132] Unless otherwise explicitly recited herein, any reference to an electronic signal or an electromagnetic signal (or their equivalents) is to be understood as referring to a non-volatile electronic signal or a non-volatile electromagnetic signal.

[00133] Recording the results from an operation or data acquisition, such as for example, recording results at a particular frequency or wavelength, is understood to mean and is defined herein as writing output data in a non-transitory manner to a storage element, to a machine-readable storage medium, or to a storage device. Non-transitory machine-readable storage media that can be used in the invention include electronic, magnetic and/or optical storage media, such as magnetic floppy disks and hard disks; a DVD drive, a CD drive that in some embodiments can employ DVD disks, any of CD-ROM disks (i.e., read-only optical storage disks), CD-R disks (i.e., write-once, read-many optical storage disks), and CD-RW disks (i.e., rewriteable optical storage disks); and electronic storage media, such as RAM, ROM, EPROM, Compact Flash cards, PCMCIA cards, or alternatively SD or SDIO memory; and the electronic components (e.g., floppy disk drive, DVD drive, CD/CD-R/CD-RW drive, or Compact Flash/PCMCIA/SD adapter) that accommodate and read from and/or write to the storage media. Unless otherwise explicitly recited, any reference herein to “record” or “recording” is understood to refer to a non-transitory record or a non-transitory recording.

THEORETICAL DISCUSSION

[00134] Although the theoretical description given herein is thought to be correct, the operation of the devices described and claimed herein does not depend upon the accuracy or validity of the theoretical description. That is, later theoretical developments that may explain the observed results on a basis different from the theory presented herein will not detract from the inventions described herein.

INCORPORATION BY REFERENCE

[00135] Any patent, patent application, patent application publication, journal article, book, published paper, or other publicly available material identified in the specification is hereby incorporated by reference herein in its entirety. Any material, or portion thereof, that is said to be incorporated by reference herein, but which conflicts with existing definitions, statements, or other disclosure material explicitly set forth herein is only incorporated to the extent that no conflict arises between that incorporated material and the present disclosure material. In the event of a conflict, the conflict is to be resolved in favor of the present disclosure as the preferred disclosure.

[00136] While the present invention has been particularly shown and described with reference to the preferred mode as illustrated in the drawing, it will be understood by one skilled in the art that various changes in detail may be affected therein without departing from the spirit and scope of the invention as defined by the claims.

What is claimed is:

1. A defect detection system, comprising:
 - a hollow mechanical structure having a closed shell, the shell dividing space into an interior volume of said structure and an exterior volume outside said hollow mechanical structure;
 - at least one of:
 - (a) a first sound receiver situated within said interior volume of said hollow mechanical structure, said first sound receiver configured to receive sounds generated by the relative motion of said hollow structure and the surrounding air and to generate first electrical signals representative of said sounds; and
 - (b) a second sound receiver situated in the exterior volume outside said hollow mechanical structure and a sound generator situated within said interior volume of said hollow mechanical structure, said first sound receiver configured to receive sounds generated by said sound generator situated within said interior volume of said hollow mechanical structure and to generate second electrical signals representative of said sounds, said sound generator configured to generate sound in response to third electrical signals received by said sound generator;
 - a wireless transmitter configured to receive said first electrical signals from said first sound receiver, said second electrical signals from said second sound receiver and configured to communicate said signals to a data processing system, and configured to receive driving signals from said data processing system and to communicate the driving signals to said sound generator as said third electrical signals;
 - said data processing system configured to analyze said first and said second electrical signals to determine a result that describes whether damage or a defect is present in said closed shell of said hollow mechanical structure and configured to perform at least one of

displaying said result to a user, recording said result, and transmitting said result to another system for further processing.

2. The defect detection system of claim 1, wherein said hollow mechanical structure having a closed shell is a blade of a wind turbine.
3. The defect detection system of claim 1, wherein said defect is one or more of a hole, edge split or a crack.
4. The defect detection system of claim 1, wherein said sound generator is configured to generate sound in the range of frequencies from 50 Hz to 20 KHz.
5. The defect detection system of claim 4, wherein said sound generator is configured to generate sound in the range of frequencies from 500 Hz to 10 KHz.
6. The defect detection system of claim 4, wherein said sound generator is configured to generate sound in the range of frequencies from 1 KHz to 5 KHz.
7. The defect detection system of claim 1, wherein said sound generator is configured to generate sound in the ultrasonic frequency range.
8. The defect detection system of claim 1, wherein said wireless transmitter is configured to operate according to an IEEE protocol for wireless transmission.
9. The defect detection system of claim 1, wherein said wireless transmitter and said data processing system are configured to communicate using the Internet.
10. The defect detection system of claim 1, wherein said data processing system is a cloud-based data processing system.

11. The defect detection system of claim 1, wherein said data processing system comprises a general purpose programmable computer that operates under the control of instructions recorded on a machine readable medium.

12. A defect detection method, comprising the steps of:

providing a defect detection system, comprising:

a hollow mechanical structure having a closed shell, the shell dividing space into an interior volume of said structure and an exterior volume outside said hollow mechanical structure;

at least one of:

- (a) a first sound receiver situated within said interior volume of said hollow mechanical structure, said first sound receiver configured to receive sounds generated by the relative motion of said hollow structure and the surrounding air and to generate first electrical signals representative of said sounds; and
- (b) a second sound receiver situated in the exterior volume outside said hollow mechanical structure and a sound generator situated within said interior volume of said hollow mechanical structure, said first sound receiver configured to receive sounds generated by said sound generator situated within said interior volume of said hollow mechanical structure and to generate second electrical signals representative of said sounds, said sound generator configured to generate sound in response to third electrical signals received by said sound generator;

a wireless transmitter configured to receive said first electrical signals from said first sound receiver, said second electrical signals from said second sound receiver and configured to communicate said signals to a data processing system, and configured to receive driving signals from said data processing system and to communicate the driving signals to said sound generator as said third electrical signals;

said data processing system configured to analyze said first and said second electrical signals to determine a result that describes whether

damage or a defect is present in said closed shell of said hollow mechanical structure and configured to perform at least one of displaying said result to a user, recording said result, and transmitting said result to another system for further processing;

in the event that the apparatus described in paragraph (a) above is present, performing the steps of:

- receiving first electrical signals at said wireless transmitter;
- communicating said first electrical signals to said data processing system; and
- analyzing said first electrical signals to determine a result that describes whether damage or a defect is present in said closed shell of said hollow mechanical structure;

in the event that the apparatus described in paragraph (b) above is present, performing the steps of:

- providing driving signals to said sound generator as said third electrical signals to operate said sound generator;
- receiving second electrical signals at said wireless transmitter;
- communicating said second electrical signals to said data processing system; and
- analyzing said second electrical signals to determine a result that describes whether damage or a defect is present in said closed shell of said hollow mechanical structure; and

whichever of the apparatus in paragraph (a) or paragraph (b) is present, performing at least one of displaying said result to a user, recording said result, and transmitting said result to another system for further processing.

FIG. 2A Turbine Blade Crack Sensor FIG. 2B

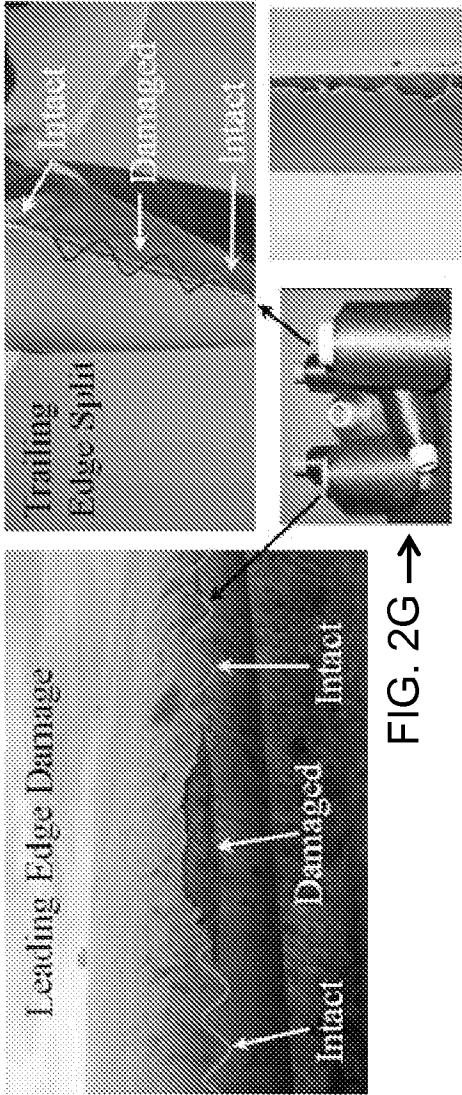


FIG. 2F

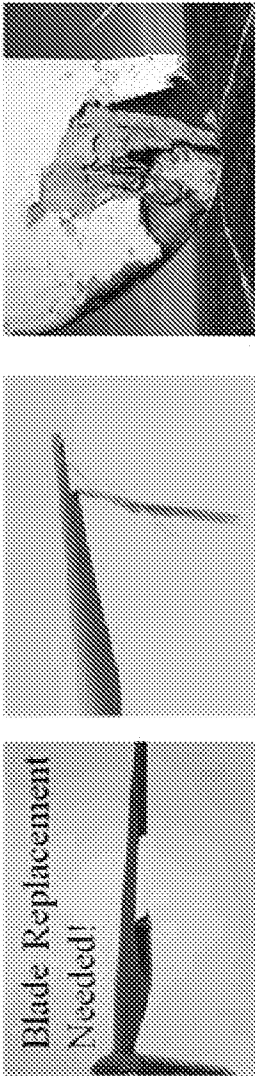


FIG. 2C FIG. 2D FIG. 2E

(all of FIGs. 2A-2G are Prior Art)

FIG. 3A

FIG. 3B

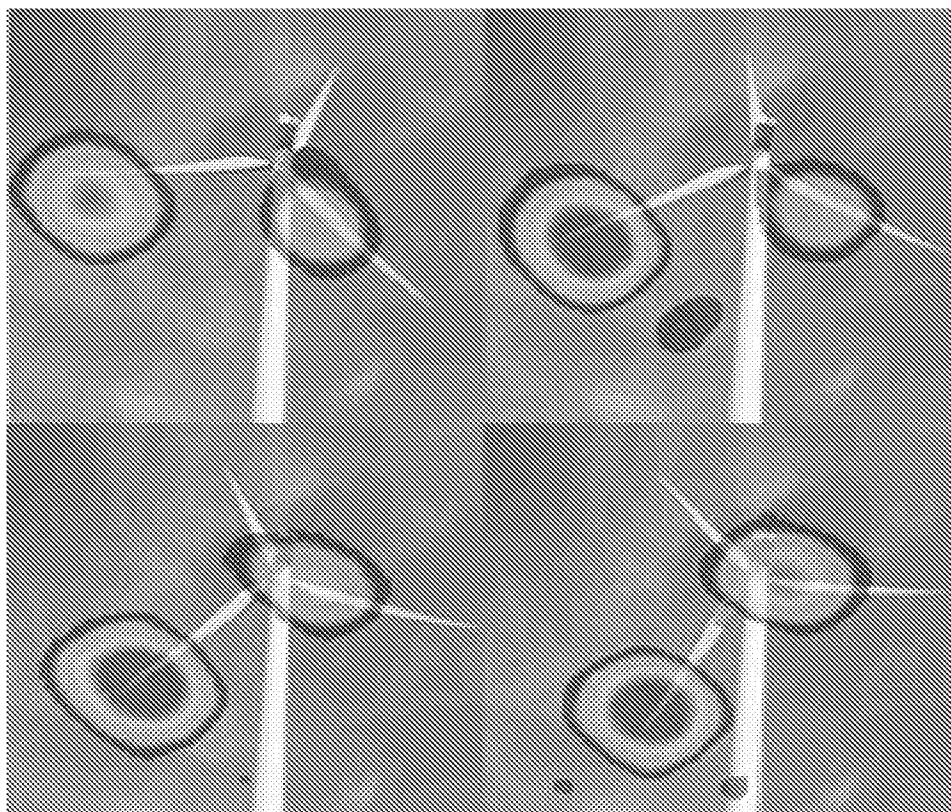


FIG. 3C

FIG. 3D

(All of FIG. 3A through FIG. 3D are Prior Art)

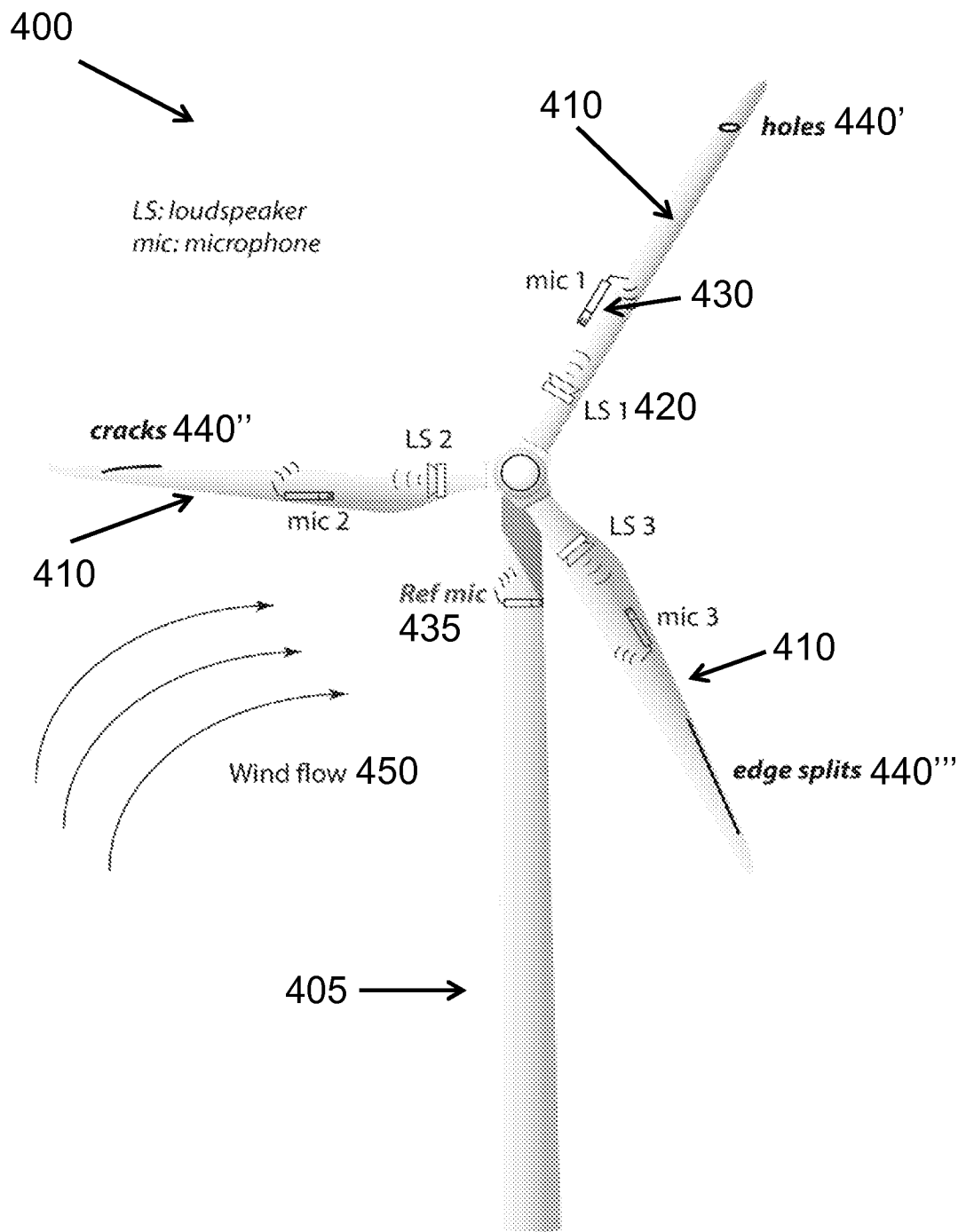


FIG. 4

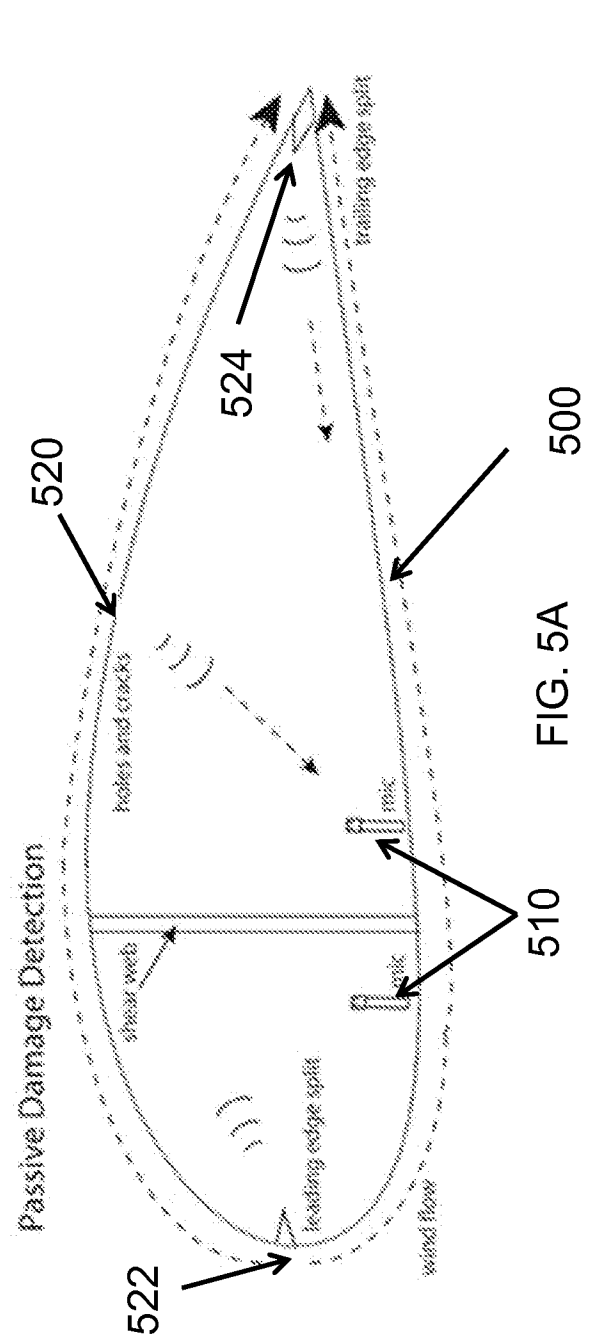


FIG. 5A

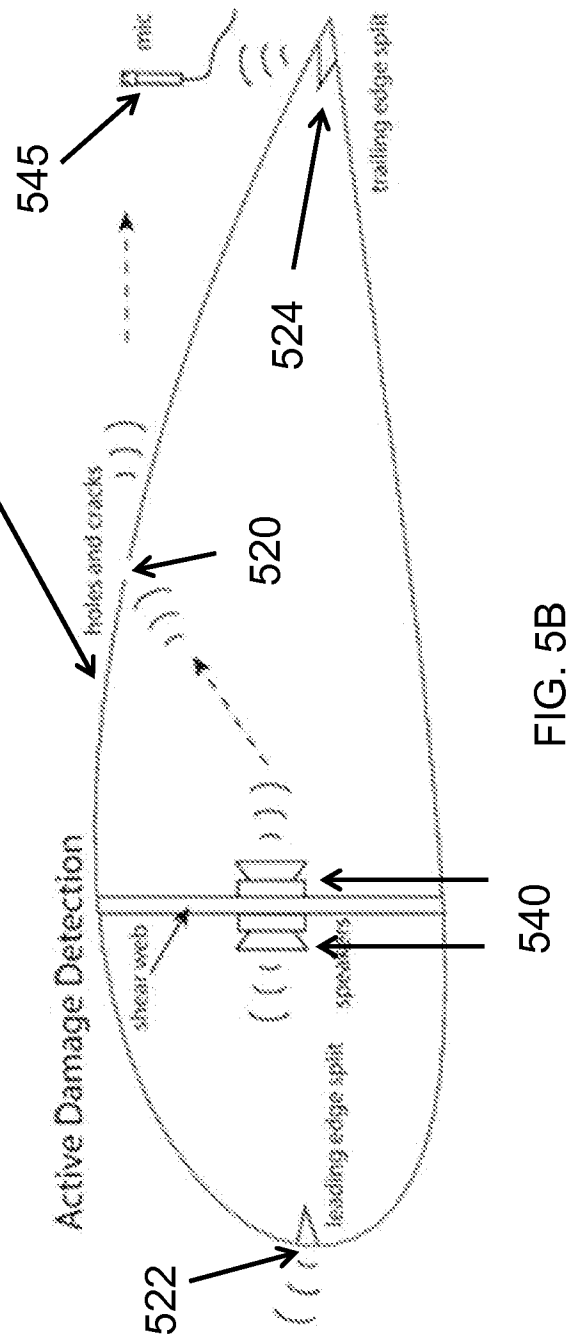


FIG. 5B

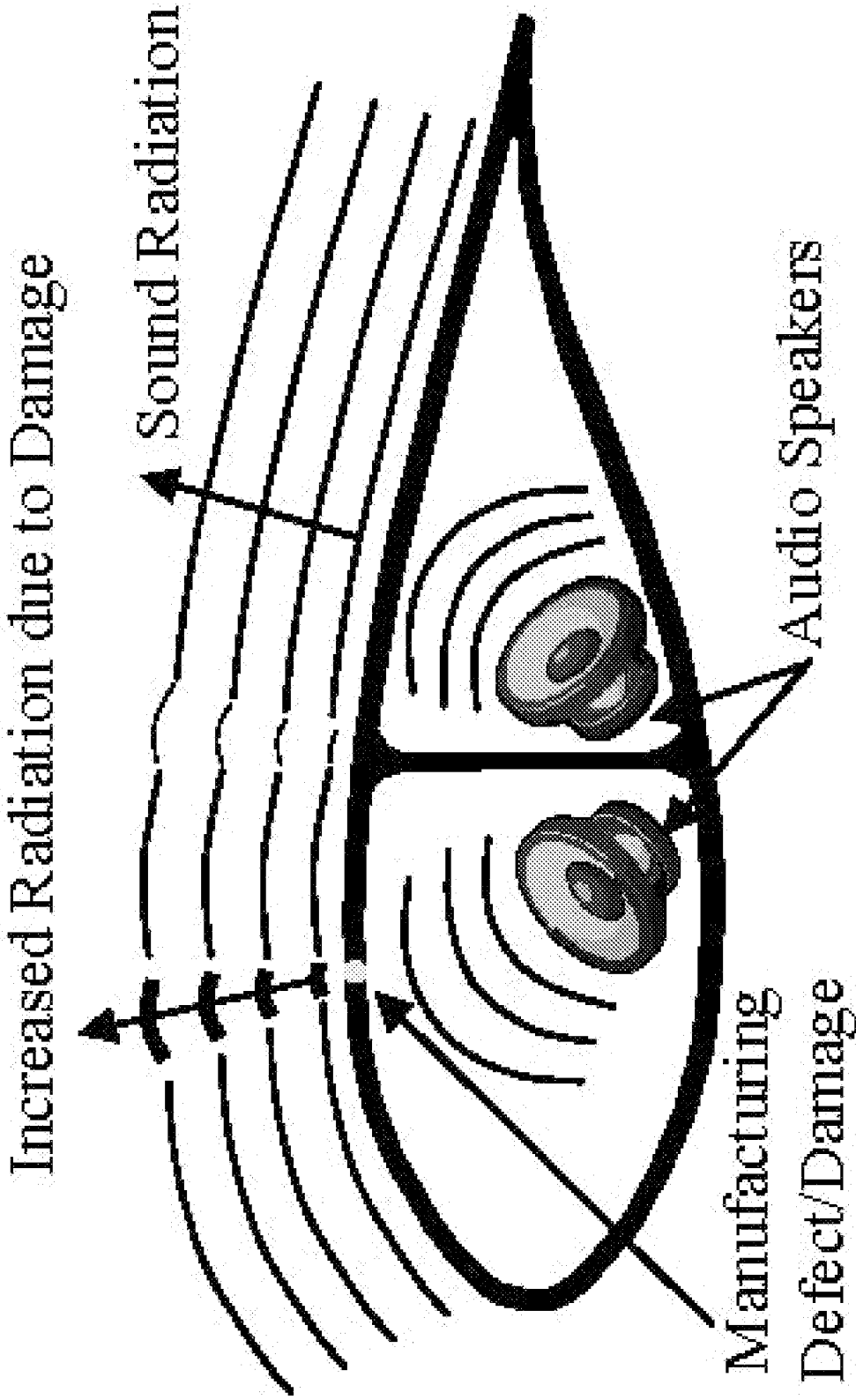


FIG. 5C

Sensor and Base Node Hardware/Software

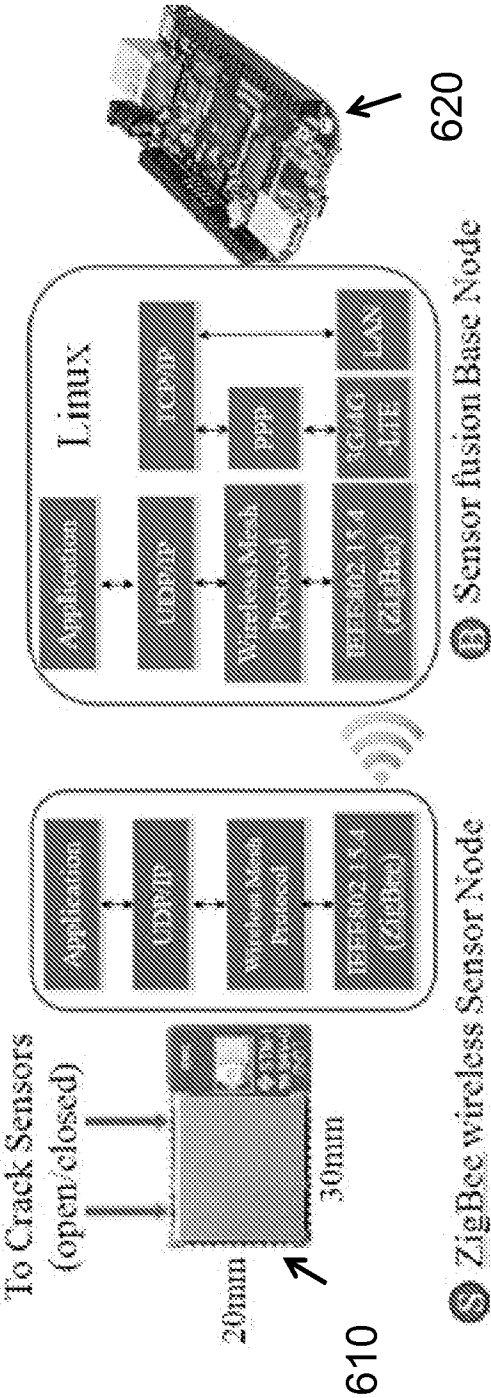


FIG. 6

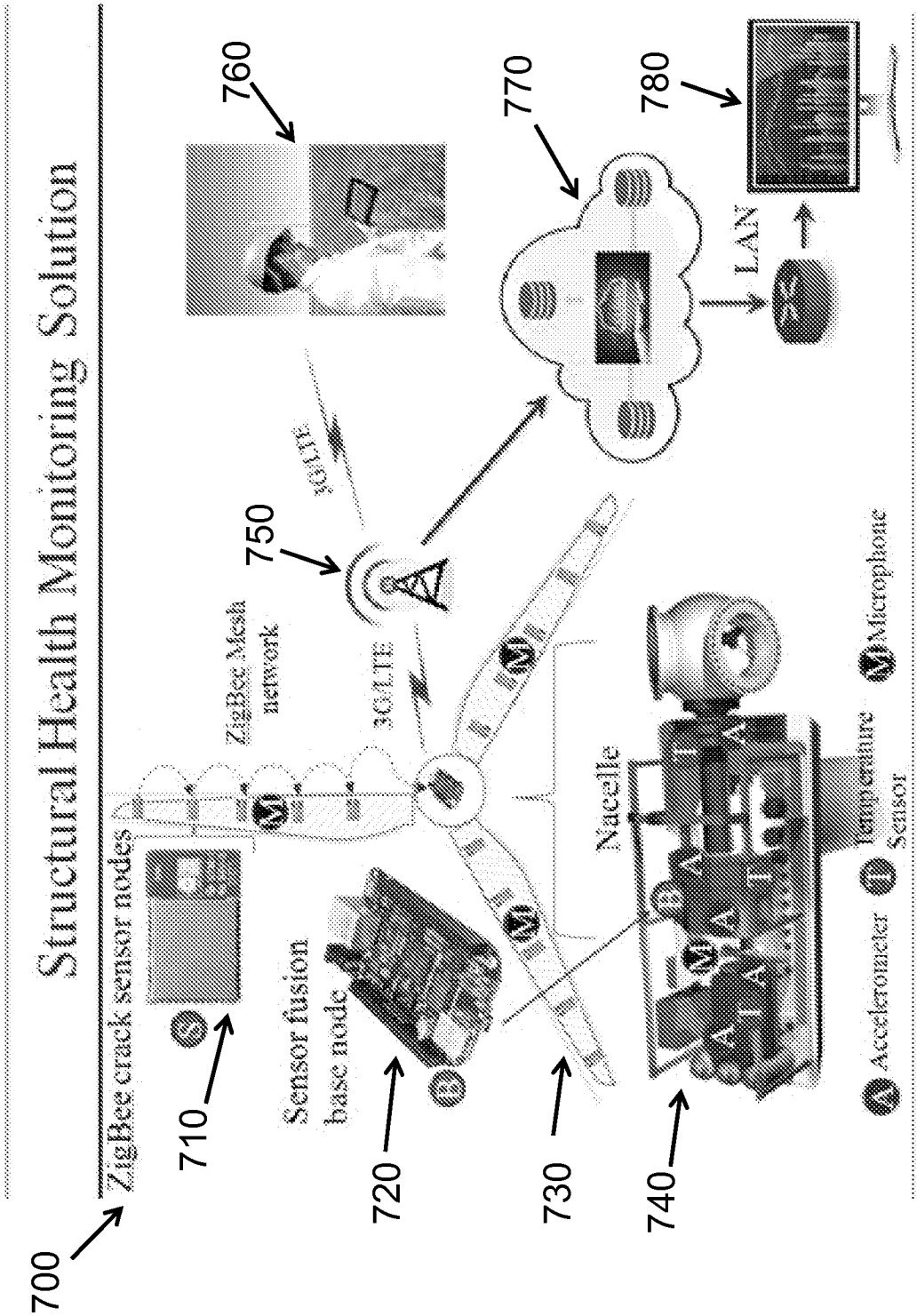


FIG. 7

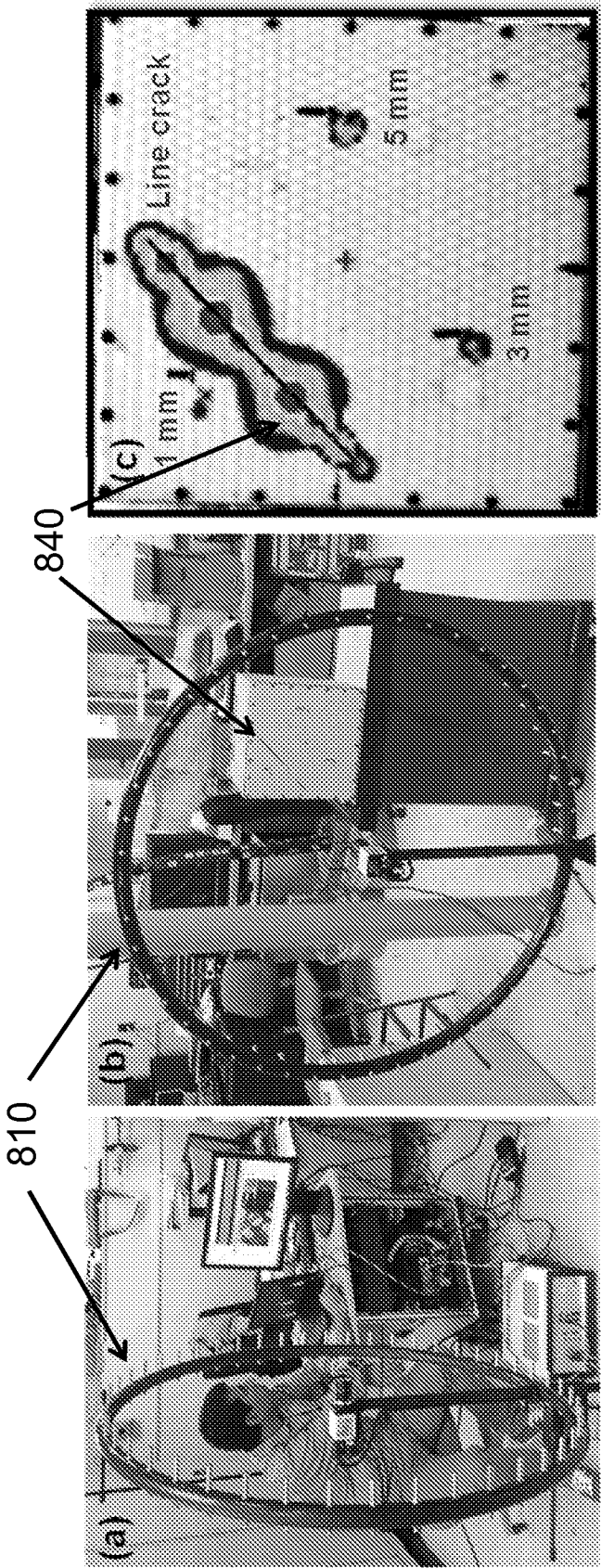


FIG. 8A

FIG. 8B

FIG. 8C

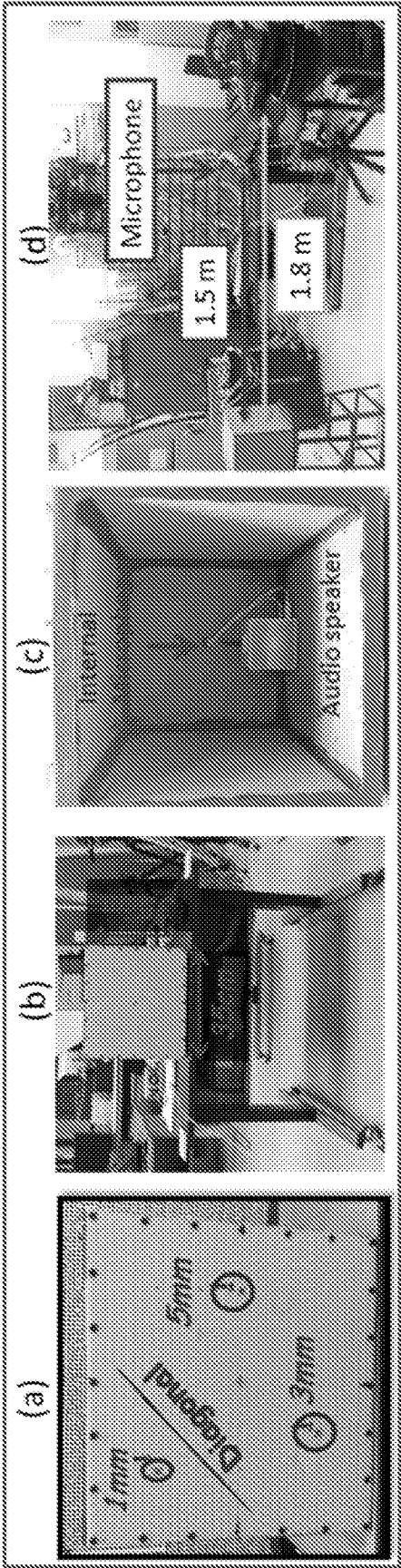


FIG. 9D

FIG. 9C

FIG. 9B

FIG. 9A

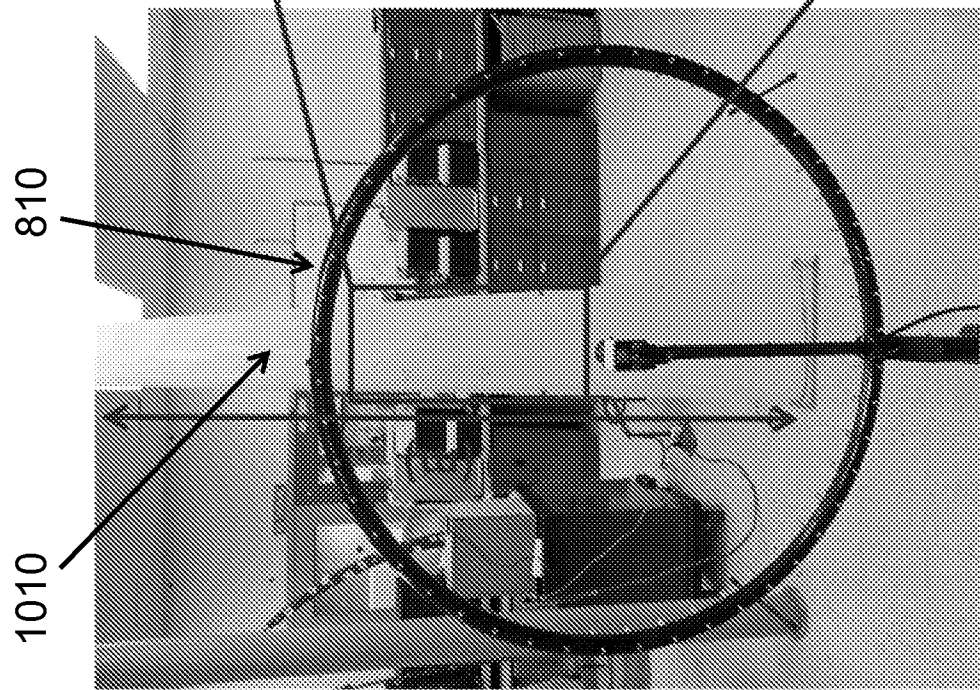


FIG. 10A

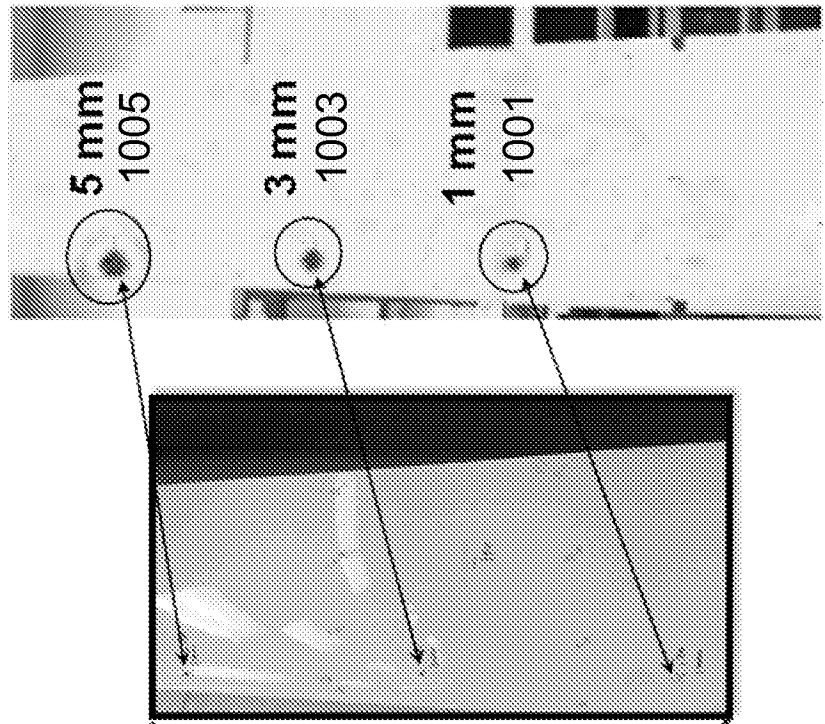


FIG. 10B

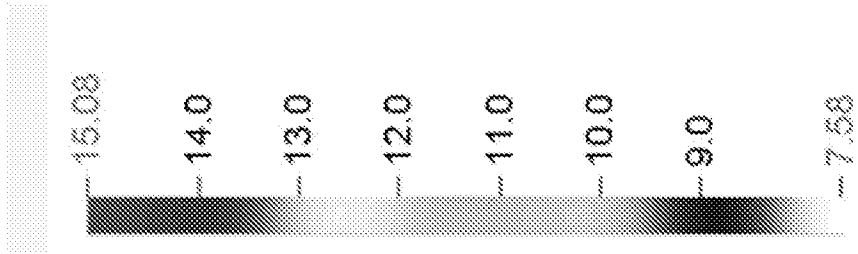


FIG. 10C

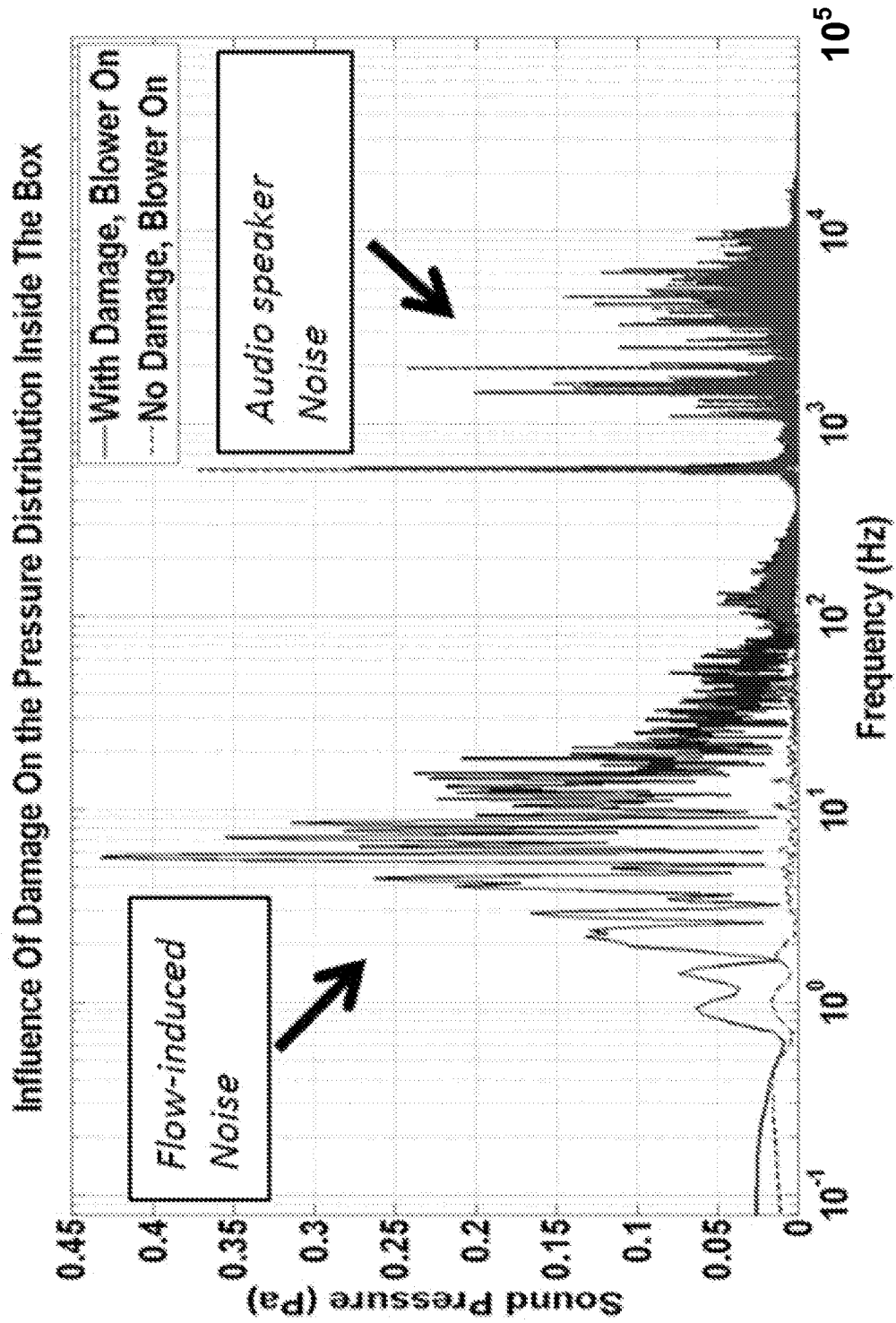


FIG. 11A

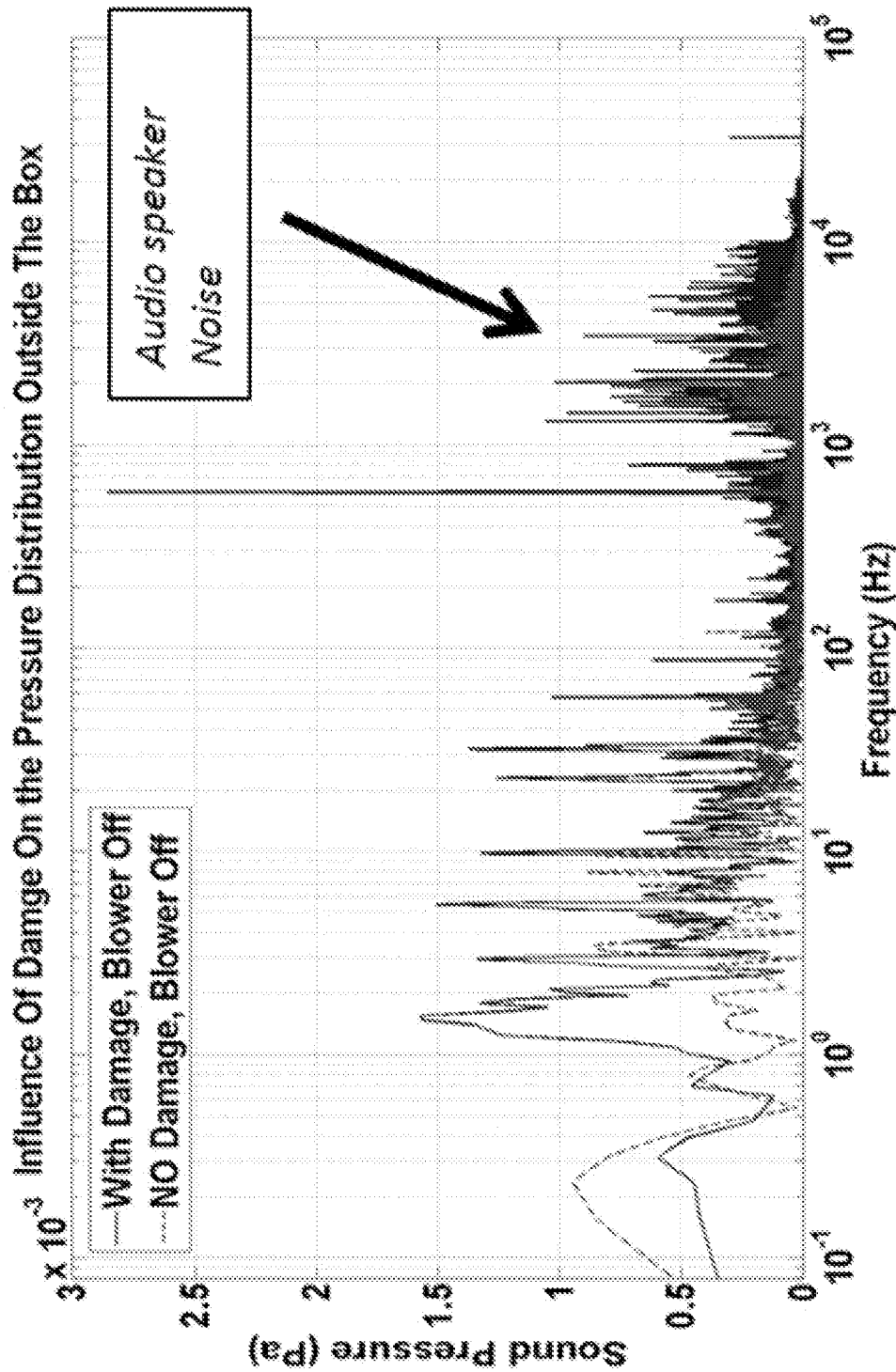


FIG. 11B

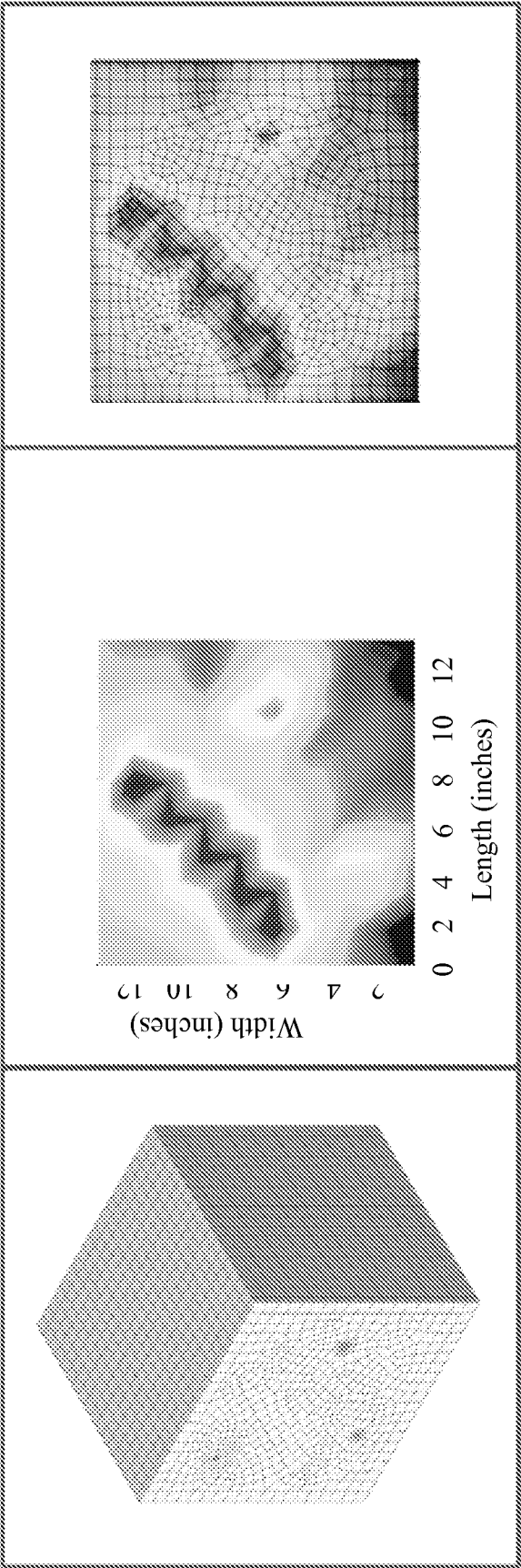


FIG. 12