

METHOD AND SYSTEM FOR CHARACTERIZING AN ELONGATED MEDIUM**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] The present application claims the priority of United States Patent Application Serial No. 63/529,539, filed on July 28, 2023, and United States Patent Application Serial No. 63/637,044, filed on April 22, 2024, the entire contents of which are incorporated herein by reference.

FIELD

[0002] The application generally relates to the field of monitoring methods, and more precisely to the field of characterizing vibro-acoustic properties of elongated media.

BACKGROUND

[0003] Monitoring pressurized fluid systems may often be challenging due to the limited access to the pipes, the complexity of the network, the size of the defects to monitor and/or detect and so on. Yet, there is an increasing demand for systems that can adequately monitor the integrity of pressurized fluid systems, as fluid loss may have negative environmental impacts (e.g. for oil and natural gas pipelines, or potable water wastes) or may lead to large loss of resources, which may be the case for aging water canalization networks across the world. Originally, methods relying on human inspection of the structure were performed, but infrastructure nowadays requires more innovative methods.

[0004] Methods relying on the detection of acoustic waves have been developed to identify defects in a pipeline network. As such, an acoustic wave may be generated by a source at a given point on an outer wall of a pipe, and an acoustic detector may sense the wave at another point after having propagated in the pipe from the source to the detector. By measuring a delta time for the wave to propagate from the source to the detector, and considering properties of the pipe, it may be possible to estimate the structural integrity of a pipe segment between the source and the detector or between two detectors. However, such methods often lack accuracy and may not provide sufficient details as the type, size or materiality of defects in the pipe. Other solutions relying on electromagnetic systems for detecting defects have been developed in order to improve the accuracy and the number of

details on the defect. Yet, such methods are often invasive, disruptive, costly and/or are limited to large-diameter pipes network.

SUMMARY

[0005] In accordance with a first aspect, there is provided a method for characterizing a dynamic behavior of an elongated medium, the method comprising: generating an input wave signal at an input location along the elongated medium, the input wave signal including a vibro-acoustic wave signal and being selected to excite a mode of vibration in the elongated medium; measuring a first output wave signal at a first location along the elongated medium spaced apart from the input location, and generating a first electrical signal based thereof, the first electrical signal indicative of a first component of the first output wave signal; measuring a second output wave signal at a second location along the elongated medium spaced apart from the input location and from the first location, and generating a second electrical signal based thereof, the second electrical signal indicative of a second component of the second output wave signal; comparing the first and second components of the mode of vibration to one another based on the first and second electrical signals; and computing a dynamic response of the elongated medium based on said comparing.

[0006] Further in accordance with the above aspect, for example, the input wave signal is selected to target a structural natural frequency of the elongated medium to induce a resonance on a predefined frequency band.

[0007] Further in accordance with the above aspects, for example, the method further includes measuring the input wave signal at the input location and generating a third electrical signal based thereof, the third electrical signal indicative of a third component of the input wave signal, wherein said comparing further includes comparing the third component of the input wave signal on the third electrical signal with the first and second components of the first and second output wave signals on the first and second electrical signals.

[0008] Further in accordance with the above aspects, for example, the method further includes obtaining an analytical model of the elongated medium including at least estimated tonal properties of the elongated medium, wherein the input wave signal is defined by the estimated tonal properties.

[0009] Further in accordance with the above aspects, for example, the method further includes generating an experimental model of the elongated medium based on the first and second signals; and updating the analytical model based on the experimental model, wherein said computing the dynamic response is performed using the analytical model and/or the experimental model.

[0010] Further in accordance with the above aspects, for example, the method further includes associating a quality indicator with the generated experimental model, the quality indicator including a given value of a signal to noise ratio, a presence of an input signal in the measured output signals, and/or a given value of coherence between output signals.

[0011] Further in accordance with the above aspects, for example, said generating the experimental model comprises conducting a modal analysis of the elongated medium and using the modal analysis in said obtaining the analytical model.

[0012] Further in accordance with the above aspects, for example, conducting the modal analysis includes predicting, using non-linear functions, a dynamic behavior of the elongated medium at virtual positions beyond regions delimited between the input location and the first and second locations.

[0013] Further in accordance with the above aspects, for example, the method further includes dividing the dynamic response into a plurality of time windows; and obtaining a dynamic response of the elongated medium for each one of the plurality of time windows.

[0014] Further in accordance with the above aspects, for example, said obtaining the dynamic response for each one of the plurality of time windows includes calculating a signal average over a given frequency bandwidth.

[0015] Further in accordance with the above aspects, for example, said comparing includes computing a cross-correlation of the first and second electrical signals; computing a cross-correlation of the first and second electrical signals with the third electrical signal; computing transfer functions between the first and second electrical signals and the third electrical signal; and/or computing a predictive transfer function of the elongated medium between the first and second electrical signals based on the computed transfer functions.

[0016] Further in accordance with the above aspects, for example, said comparing includes normalizing the predictive transfer function of the elongated medium with the computed transfer functions.

[0017] Further in accordance with the above aspects, for example, the method further includes displaying the first and second output wave signals on a user interface, and/or displaying a visual indication on the user interface in response to determining an acquisition quality indicator of the measured first and second output wave signals.

[0018] Further in accordance with the above aspects, for example, said generating the input signal includes generating a set of tones, the set of tones being sequentially selected in frequency or in a predefined pattern.

[0019] Further in accordance with the above aspects, for example, said generating the input wave signal includes selecting a first input wave signal to excite the elongated medium in an axial shell dominated wave frequency range and/or a fluid dominated wave frequency range.

[0020] Further in accordance with the above aspects, for example, said computing the dynamic response is performed solving a mathematical model including the following equations:

$$k_1^2 = k_f^2 \left(1 + \frac{\frac{2B_f}{a}}{\left(\frac{Eh}{a^2}\right) - \rho h \omega^2} \right)$$

$$k_2^2 = k_L^2 \left(1 + \frac{\nu^2}{1 - \nu^2} \frac{\frac{Eh}{a^2}}{\left(\frac{Eh}{a^2}\right) + \left(\frac{2B_f}{a}\right) - \rho h \omega^2} \right)$$

where k_L , k_f , k_1 k_2 are the compressional, fluid, fluid dominated wave and axial shell dominated wave wavenumbers, respectively, ν is the Poisson ratio of the elongated medium, a is the radius of the elongated medium, B_f is the bulk modulus of external media, E is the Young's modulus of the elongated medium, h is a wall thickness, ρ is the density of the shell material and ω is the angular frequency.

[0021] Further in accordance with the above aspects, for example, the method further includes plotting a stiffness profile of the elongated medium, wherein said plotting includes: normalizing the stiffness profile based on a nominal stiffness of the elongated medium; plotting the normalized stiffness profile of the elongated medium to provide a visualization mean to identify a stiffness differential between the nominal stiffness and the stiffness profile along the elongated medium; and/or plotting the Young's modulus, the density, the Poisson ratio, the wall thickness and/or a diameter of the elongated medium.

[0022] Further in accordance with the above aspects, for example, said computing includes subtracting the third electrical signal from first and second electrical signals.

[0023] Further in accordance with the above aspects, for example, the first component of the first output wave signal and/or the second component of the second output wave signal each include a modal frequency.

[0024] In accordance with a second aspect, there is provided a system for characterizing an elongated medium, the system comprising: a wave generator configured for generating a vibro-acoustic wave, the vibro-acoustic wave being selected to excite a mode of vibration in the elongated medium; a plurality of sensing units attached to the elongated medium at different locations, each sensing unit having: a sensor for detecting and measuring an output wave signal at an output location along the elongated medium, and a processing unit for transducing the measured output wave signal into an electrical signal; and a computing device communicatively coupled to the plurality of sensing units, the computing device having a processing unit and a memory having stored thereon program instructions executable by the processing unit for: receiving the electrical signal of each one of the plurality of sensing units, the output wave signals including the excited mode of vibration; generating an analytical model of the elongated medium; and computing a dynamic behavior of the elongated medium by comparing the analytical model with the electrical signal of each one of the plurality of sensing units.

[0025] Further in accordance with the above aspects, for example, each sensing unit further includes a geolocation identifier for identifying a geolocation of the sensing unit, and wherein the program instructions further include: receiving the geolocation of each sensing unit via the

geolocation identifier; and computing the dynamic behavior using the geolocation of each sensing unit.

[0026] In accordance with a third aspect, there is provided a system for characterizing an elongated medium. The system includes a wave generator configured for generating a vibro-acoustic wave in the elongated medium, a plurality of sensing units attached to the elongated medium at different locations and a computing device communicatively coupled to the plurality of sensing units. Each sensing unit has a geolocation identifier for identifying the geolocation of the sensing unit, a sensor for detecting and measuring the vibro-acoustic wave at an output point along the elongated medium and a processing unit for transducing the measured vibro-acoustic wave into an output signal. The computing device has a processing unit and a memory having stored thereon program instructions executable by the processing unit for receiving the output signal of each one of the plurality of sensing units and the geolocation thereof, generating an analytical model of the elongated medium and computing a dynamic behavior of the elongated medium by comparing the analytical model with the measured output signals and the geolocation thereof.

[0027] In accordance with a fourth aspect, there is provided a method for experimentally characterizing a pressurized fluid system, the method comprising: inputting one or more test input signals at an input point, the one or more test input signals having a duration at least longer than a period needed to propagate across the pressurized fluid system; measuring output signals from a respective first and at least second output points distanced from the input point; computing a cross-correlation of the output signals, thereby obtaining a dynamic response of the pressurized fluid system; dividing the dynamic response into a plurality of time windows; and obtaining a dynamic response of the pressurized fluid system for each of time windows.

[0028] In accordance with a fifth aspect, there is provided a method for analyzing data for a system for characterizing an elongated medium, the method comprising: receiving a measured input signal from an input location along the elongated medium; receiving a plurality of output signals from selected locations distanced from the input location along the elongated medium; processing the plurality of output signals, and generating an experimental model of the elongated medium based at least on the plurality of output signals and the input signal; and computing a dynamic behavior of the elongated medium from the experimental model.

[0029] In accordance with a sixth aspect, there is provided a method for rectifying an analytical model for characterizing an elongated medium, the method comprising: receiving analytical properties of the elongated medium; generating an analytical model of the elongated medium using the analytical properties thereof, the analytical model including at least estimated tonal properties of the elongated medium; generating a vibro-acoustic wave adapted to excite the elongated medium, the vibro-acoustic wave defined at least by the estimated tonal properties of the analytical model of the elongated medium; propagating the generated vibro-acoustic wave in the elongated medium; receiving a plurality of output signals extracted at selected locations along the elongated medium; processing the plurality of output signals and a measured input signal of the vibro-acoustic wave from an input location, and generating an experimental model of the elongated medium based on the plurality of output signals and the measured input signal; computing a dynamic behavior of the elongated medium from the experimental model; and updating the analytical model using the computed dynamic behavior.

[0030] In accordance with a seventh aspect, there is provided a method for experimentally characterizing a pressurized fluid system, the method comprising: inputting one or more test input signals at an input point; measuring the one or more test input signals from the input point; measuring output signals from a respective first and at least second output points distanced from the input point; computing a cross-correlation of the output signals; computing a cross-correlation of each output signal with the measured one or more test input signals; computing transfer functions between each output signal and the measured one or more test input signals; computing a predictive transfer function of the pressurized fluid system between the output signal at the second output point and the output signal at the first output point based on the transfer function between the output signal at the first output point and the one or more test input signals; and normalizing the predictive transfer function of the pressurized fluid system with the transfer function between the output signal at the second output point and the one or more test input signals.

[0031] In accordance with a eighth aspect, there is provided a method for characterizing dynamically an elongated medium, the method comprising: selecting a first input signal to excite the elongated medium at least in an axial shell dominated wave frequency range, generating the first input signal via a wave generator operatively coupled with the elongated

medium, sensing the first input signal at an input location and a first set of output signals at respective output locations along the elongated medium, processing the measured first set of output signals and the measured first input signal, including solving a mathematical model; and generating a first experimental model of the elongated medium based on the solved mathematical model.

[0032] Many further features and combinations thereof concerning embodiments described herein will appear to those skilled in the art following a reading of the instant disclosure.

DESCRIPTION OF THE FIGURES

[0033] Fig. 1 is a schematic view of a system for characterizing an elongated medium, in accordance with one or more embodiments;

[0034] Fig. 2 is a schematic view of a sensing unit of the system of Fig. 1, in accordance with an embodiment;

[0035] Fig. 3 illustrates an embodiment of the system of Fig. 1 for characterizing an elongated medium, in accordance with an embodiment;

[0036] Fig. 4 illustrates another embodiment of the system of Fig. 1 for characterizing an elongated medium, in accordance with an embodiment;

[0037] Fig. 5 is a flow chart of a method for analyzing data implementable by the system of Fig. 1 for characterizing an elongated medium, according to an embodiment;

[0038] Fig. 6 is a flow chart of a method for rectifying an analytical model for characterizing an elongated medium, according to an embodiment;

[0039] Fig. 7 is a flow chart of a method for experimentally characterizing a pressurized fluid system, according to an embodiment;

[0040] Fig. 8 is a block diagram of an exemplary computing device of the system of Fig. 1, in accordance with an illustrative embodiment;

[0041] Fig. 9 is a first exemplary dynamic response profile, in accordance with an embodiment;

[0042] Fig. 10 is a second exemplary dynamic response profile, in accordance with an embodiment;

[0043] Fig. 11 is a third exemplary dynamic response profile, in accordance with an embodiment; and

[0044] Fig. 12 is a fourth exemplary dynamic response profile, in accordance with an embodiment.

DETAILED DESCRIPTION

[0045] Referring to Fig. 1, there is shown a schematic illustration of an embodiment of a system 100 for characterizing an elongated medium 102. In operation, the system 100 may characterize the dynamic behavior of the elongated medium 102 using vibro-acoustic wave generation and measurements. The system 100 comprises a wave generator 104 configured for generating a vibro-acoustic wave in the elongated medium 102, and a plurality of sensing units 200a,b,c operatively coupled to the elongated medium 102 at selected locations along the elongated medium 102 to sense the generated vibro-acoustic wave that is propagating therein. The sensing units 200a,b,c are communicatively coupled to a computing device 106 for processing measurements obtained by the sensing units 200a,b,c. In at least some embodiments, the computing device 106 is in communication with a user interface 108. In at least some embodiments, the computing device 106 is in wireless communication with the sensing units 200a,b,c via a wireless network 110. The wireless network may be, for instance, the Internet, a local-area network (LAN), a personal-area network (PAN), a metropolitan-area network (MAN), a wide-area network (WAN), and the like. Wired communication between the sensing units 200a,b,c and the computing device 106 may also be contemplated. Features of the computing device 106 will be described later with respect to an exemplary computing device 800 with reference to Fig. 8.

[0046] It will be appreciated that the present technology is directed to the field of vibro-acoustics, which lies at the interface of acoustics and structural dynamics. Generation, propagation and measurement of vibro-acoustic wave may be performed in both solid and fluid media. As such, the present technology is not limited to fluids, which is generally the case for acoustic waves.

[0047] The elongated medium 102 is composed at least partially of a material dynamically responsive to the propagation of vibro-acoustic waves, such as steel, iron, copper and/or any suited alloy. In at least some embodiments, the elongated medium 102 may include plastic such as polyvinyl chloride (PVC) as other possibilities. In at least some embodiments, the elongated medium 102 is a prestressed concrete pipe made of a concrete and optionally of steel wires configured for providing tensile stresses to the pipe. The concrete pipe may be wire-wrapped, asbestos cement or any other type of concrete pipe, e.g., prestressed concrete pressure pipe (PCCP) having a steel core cylinder with concrete layers inside and outside. It will be appreciated that various other types of material not listed herein may be subject to the present technology.

[0048] The elongated medium 102 may have various shapes depending on the application. In at least some embodiments, the elongated medium 102 has a tubular shape, which may have cylindrical cross-section or other possible cross-section such as oval, obround, square, circle, rectangular, hexagonal or other polygonal shape. The diameter (or other transverse dimensions) and wall thickness may be constant or vary along an elongation axis X. In at least some embodiments, the elongated medium 102 is configured to contain pressurized fluid therein. In at least some embodiments, the elongated medium 102 is a pipe of a pressurized network, such as a pipeline network or an aqueduct network. In other embodiments, the elongated medium 102 may be a sound-propagating section or a beam of a structure underground or above the ground surface.

[0049] The wave generator 104 is operatively coupled to the elongated medium 102. The wave generator 104 is configured to generate an input signal 112 in the form of a vibro-acoustic wave that, in use, propagates in the elongated medium 102. The wave generator 104 is an electronic device that may generate a vibro-acoustic wave by selecting and/or controlling various properties of a wave signal, including the amplitude(s), the frequency(ies), the duration(s) and the shape thereof. The wave generator 104 may include a function generator, an arbitrary waveform generator, a radiofrequency (RF) generator, a microwave generator, an analog signal generator, an audio-frequency (AF) signal generator, a vector signal generator, a digital pattern generator, or the like. In at least some embodiments, the wave generator 104 may be portable. Compactness and weight of the wave generator 104 may be adapted to facilitate handling by an operator. This may be particularly advantageous to transport the wave

generator 104 between test sites, with limited equipment or workforce. In some alternatives, a modal hammer may be used to excite the elongated medium 102 in addition to the wave generator 104. As shown in Fig. 1, and as will be further described below, the wave generator 104 may be configured for generating propagating vibro-acoustic waves 114 along the elongated medium 102. In response to the generated vibro-acoustic waves 114, the elongated medium 102 may enter in a state of resonance, thereby generating other propagating waves of various harmonics or stationary waves 114, or a combination thereof.

[0050] The generated input signal 112 may be defined by a complex function including one or more sinusoids or other waveforms of different timing, frequencies and/or amplitudes. Generally, the input signal 112 has a duration longer than the time needed to propagate through the elongated medium 102. The generated input 112 signal may also include one or more step-function, and/or one or more impulse function. In at least some embodiments, the wave generator 104 is configured to operate at frequencies in the range of 5 to 2000 Hz, which may be a range suited for characterizing pipes. In other embodiments where the elongated medium 102 is a medium other than a pipe, the frequency range may vary and may span a higher range, e.g., up to 10 kHz or higher. The elongated medium 102 may act as a vibro-acoustic filter. Stated otherwise, within some frequency bands, the elongated medium 102 may not influence the vibro-acoustic waves. At some specific frequencies or within specific frequency bands, the elongated medium 102 may induce changes to a vibro-acoustic wave travelling therein. The vibro-acoustic wave propagates in the elongated medium 102 and may "store" or "carry" structural information associated with the elongated medium 102 that vibrates. The generated input signal 112 may thus act as a carrier of the information to be extracted from the excited elongated medium 102. The generated input signal 112 may thus be referred to as a carrier signal. In order to carry the most efficiently the information, the vibro-acoustic properties and/or dynamic response of the elongated medium 102 may be accounted for in the generation of a suitable vibro-acoustic wave. In other words, a generated input signal 112 that is adapted to the dynamic response of the elongated medium 102 is therefore contemplated. The dynamic response of the elongated medium 102 may be determined via a modal analysis. The modal analysis may allow to identify the specific frequencies (or eigenfrequencies) and the associated shape of deformation of the elongated medium 102. The modal analysis may be performed via finite elements simulations or experimentally

through measurements, as will be further described later. The vibro-acoustic waves may be specifically selected (“tuned” or “built”) to excite the elongated medium 102 by varying the frequency information of the excitation waves, the type of excitation, the duration, etc. The generated vibro-acoustic waves may be refined iteratively until a desired quality of the signal sensed at the sensing units 200a,b,c is obtained, as will be further described later. It will be understood that the term “vibro-acoustic properties” used herein may be representative of the properties of the dynamic response (which may be referred to as “dynamic properties”), and vice-versa.

[0051] The input signal 112 may include one or more sets of tones, i.e., sets of given frequencies, as a way of exciting the elongated medium 102 dynamically. The length of the tones in time is generally longer than the time needed for the tones to propagate through the elongated medium 102. In this case, the entirety of the elongated medium 102 is excited by the tones simultaneously. In practice, a plurality of tones of different frequencies may be sequentially provided to the elongated medium 102 to create various types of excitation patterns. By measuring the correlation between the output signals measured by the sensing units 200a,b,c, it is possible to obtain different structural information respective to excitation patterns created by corresponding tones. It will be appreciated that using tones to excite the elongated medium 102 and measuring the output signals at a plurality of locations on the elongated medium 102 is generally suited for characterizing non-linear systems.

[0052] In at least some embodiments, the tones are obtained from a dictionary (also called “library”) comprising a plurality of tones selected to create a variety of excitation patterns in the elongated medium 102. In a case where the elongated medium 102 is characterized iteratively and/or the vibro-acoustic waves refined iteratively, the first iteration may include exciting the elongated medium 102 with vibro-acoustic waves including the entirety of the dictionary. For the next iterations, tones may be selected in the dictionary to extract specific structural information from the elongated medium 102 obtained in the first iteration without needing to reproduce the entire dictionary. The dictionary may be generic, i.e., not configured for creating excitation patterns for specific types of elongated media, or specific to the elongated medium 102 subject to the characterization. In the latter case, the dictionary may be created based on analytical and/or experimental modeling of the elongated medium 102, as will be described hereinafter.

[0053] In one specific embodiment, the input signal 112 is a pre-defined signal formed of intervals of tones and no signal periods performed sequentially. For instance, the input signal 112 may include a 20 Hz tone played for five seconds, followed by a ten seconds of no signal, followed by a 40 Hz tone played for five seconds, followed by a ten seconds of no signal, followed by a 60 Hz tone played for five seconds, followed by a 80 Hz tone played for five seconds, followed by a ten seconds of no signal followed by a 100 Hz tone played for five seconds, followed by a ten seconds of no signal followed by a 120 Hz tone played for five seconds, followed by a ten seconds of no signal.

[0054] These pre-defined signals may be used for a plurality of elongated media, and thus be considered generic.

[0055] It will be understood that the present disclosure is not limited to tones, as the input signal 112 may include other types of signals. In one embodiment, the input signal 112 includes a broadband signal in which a plurality of tones are convoluted.

[0056] In other embodiments, the input signal 112 includes a sweep signal having a continuous increase in frequencies. In this case, the time at each frequency is maintained is at least proportional to the wavelength at the given time. It should be understood that the time at each frequency is at least greater than the time required for the input signal 112 to propagate through the elongated medium 102. In a specific embodiment, the input signal 112 may include a sweep signal starting at 5 Hz and ending at 120 Hz with increments steps of 5 Hz and with a residence time of 5 seconds for each frequency. In another specific embodiment, the input signal 112 may include a chirp-type signal having first sweep signal starting at 5 Hz and ending at 10 Hz, a second sweep signal starting at 5 Hz and ending at 15 Hz with an increment step of 5 Hz, a third sweep signal starting at 5 Hz and ending at 20 Hz with increment steps of 5 Hz and so on.

[0057] In operation, the sensing units 200a,b,c are distributed along the elongation axis X and are spaced apart by a constant or varying distance. Such distance may be predetermined, or determinable by geolocation, as will be described later. In at least some embodiments, the sensing units 200a,b,c are positioned at the same longitudinal position between adjacent ones of them, but with a different angular position from one another, though they could have a same angular position. In operation, the sensing units 200a,b,c are configured to measure vibro-

acoustic waves propagating in the elongated medium 102. It will be appreciated that the number of sensing units 200a,b,c is not limited to the count of three (3) as depicted in Fig. 1, as any number of sensing units that is more than one (1) may apply, in accordance with various embodiments. The sensing units 200a,b,c will be further described hereinafter.

[0058] Each of the sensing units 200a,b,c are communicatively coupled to the computing device 106. The computing device 106 is configured to receive signals indicative of a vibro-acoustic property, or dynamic response, from the sensing units 200a,b,c. Another way of expressing this is that the computing device 106 is configured to receive signals from the sensing units 200a,b,c, from which vibro-acoustic properties of the elongated medium 102 may be derived. Such signals will be referred to herein as signal outputs that may be used as part of a single input multiple outputs (SIMO) characterization of the elongated medium 102, as will be further described hereinafter. The computing device 106 may be in wired communication with one or more of the sensing units 200a,b,c, or in wireless communication. In some embodiment where the computing device 106 is in communication with a user interface 108, the latter may be, for instance, a mobile device such as a tablet or smart phone, in order to monitor and/or visualize the signals received from the sensing units 200a,b,c. Visualization of the signals may be in the form of one or more graphs, diagrams (e.g., cross-correlation spectrograms), or other visual representation, and/or a visual indicator, such as an icon or other identifier indicative of a presence or absence, and/or acquisition quality indicator of one or more of the output signals from the sensing units 200a,b,c. Indication of the quality of a signal may be, e.g., a given value of a signal to noise ratio, the presence of an input signal 112 in the measured signal, a given value of coherence between signals measured at different outputs and the like. If such indications are not obtained by the computing device, a prompt may be provided to the user interface 108 indicating that the quality of the signal is not sufficient for representative measurements. In at least some embodiments, the computing device 106 may form part of the user interface 108 (or vice versa) or part of at least one of the sensing units 200a,b,c.

[0059] Referring to Fig. 2, a sensing unit 200, such as the sensing units 200a,b,c described above, includes at least a sensor 202, and a processing unit 204. Optionally, the sensing unit 200 may include a geolocation identifier 206. The sensing unit 200 is configured for acquisition of a dynamic response of the elongated medium 102 excited by the input signal

112 generated by the wave generator 104. In at least some embodiments, the sensor 202 is configured to create an impedance matching at a contact point between the sensing unit 200 and the elongated medium 102. In other embodiments, the impedance matching is created between the wave generator 104 and the elongated medium 102. The sensing unit 200 may have a data storage functionality so as to store at least part of the data associated with the measured dynamic response in the processing unit 204. Such data may be communicated via the output signals from the sensing unit 200. It should be understood that the sensor 202 and the processing unit 204 may be integrated together, i.e., not necessarily distinct components of the sensing unit 200.

[0060] The sensor 202 is configured to detect and measure vibro-acoustic waves. In operation, the sensor 202 is configured for transducing a vibro-acoustic wave propagating at the surface or in the bulk of the elongated medium 102 and measured at an output point, into an electric signal. In at least some embodiments, the sensor 202 may include a surface acoustic wave (SAW) sensor, a quartz crystal microbalance (QCM) and/or a film bulk acoustic wave resonator (FBAR). In at least some embodiments, the sensor 202 includes a microelectromechanical system (MEMS). In at least some embodiments, the sensor 202 may include an array of transducers. Other sensors 202 suitable to measure vibro-acoustic wave may be implemented in the sensing unit 200. For example, in at least some embodiments, the sensor 202 includes an accelerometer such as a piezoelectric sensor. In other embodiments, the sensor 202 includes a dynamic response sensor such as a displacement sensor, a velocity sensor, a strain gauge and the like.

[0061] The vibro-acoustic wave measured by the sensor 202 is processed into an output signal (described above), which may be stored in the processing unit 204 and/or conveyed to the computing device 106. The output signal is representative of the vibro-acoustic properties of the elongated medium 102 or allows to derive such vibro-acoustic properties via processing. The output signal is thereafter retrievable by the computing device 106.

[0062] The geolocation of the sensing unit 200 may be required for obtaining a geographical mapping of the dynamic behavior of the elongated medium 102. As described above, the sensing unit 200 may include a geolocation identifier 206, preferably a global positioning system (GPS) antenna or node for obtaining the geolocation coordinates of the sensing unit 200. The coordinates may allow to measure a distance between respective

locations of the sensing units 200. The sensing unit 200 may be configured to convey a geolocation signal indicative of a location of the sensing unit 200 via the geolocation identifier 206, though this is optional. In at least some embodiments, the coordinates are stored in the processing unit 204 or in the computing device 106. In other embodiments, the coordinates are obtained by associating the location of the sensing unit 200 using a map. In other embodiments, the coordinates are relative to the coordinates of other sensing units 200. In some variants, the coordinates may be obtained by measuring a distance from a reference location using, for example, a measuring wheel or a laser distance measurer.

[0063] Figs. 3 and 4 illustrate embodiments of a system 300,400 for characterizing an elongated medium 302,402. The systems 300,400 and elongated medium 302,402 may correspond to the system 100 and elongated medium 102 describe above. It should be understood that the features discussed above with respect to system 100 and elongated medium 102 similarly apply to the systems 300,400 and elongated medium 302,402 and will therefore not be repeated herein for conciseness. In Fig. 3, the system 300 includes a wave generator 304 connected to an outer surface of the elongated medium 302. In the embodiment shown, the elongated medium 302 is a pipe having pressurized fluid therein. A plurality of sensing units 200, here two, each have a sensor 202 connected thereto. As illustrated, the elongated medium 302 could have a defect 306 and a leak 308, which are represented between the two sensing units 200d,e, along an elongation axis X. In practice, such defect 306 and leak 308 may not be known prior to implementing the characterization of the elongated medium 302. It will be appreciated that, as shown, the vibro-acoustic wave generated by the wave generator 304 may propagate through the elongated medium 302 and interact with the illustrated defect 306 and the leak 308. Such interaction may alter the properties of the propagating wave, or wave "signature". The propagated vibro-acoustic wave measured at the sensing units 200 may therefore embed structural information on the elongated medium 302 that includes the alteration caused by the defect 306 and the leak 308. It will be appreciated that various other types of anomalies can be detected using the system 300, such as deformation of the elongated medium 302, mineral buildup inside and/or outside the elongated medium 302, stiffness variation in various portions of the elongated medium 302 and the like.

[0064] As illustrated in Fig. 4, in a data gathering application, the system 400 is adapted for characterizing a pipe network 402, which may be in a particular case a fire hydrant network. The system 400 includes a plurality of sensing units 200f,g,h,i,j, here five though other numbers are possible, each connected along an elongation axis X to the pipe(s) of the pipe network 402, and a wave generator 404 connected to a hydrant of the pipe network 402. In other embodiments, the wave generator 404 may be connected to other interfacing components of the hydrant network, for example an intermediary component between the wave generator 404 and the hydrant, on a pipe segment, a valve or an access chamber in fluid flow communication with the elongated medium 302 or other contact points on components serially connected to the elongated medium 302. The wave generator 404 could also be connected to a pipe of the pipe network 402 or other interface components as described above. While the system 400 is adapted to be installed on a pipe network 402 such as fire hydrant network, which includes usually a distribution watermain composed of small pipes, the system 400 may be also installed on transmission mains, which are composed of larger pipes. The present technology may thus be implemented in various sorts of pipe network, regardless of the diameter of the pipe.

[0065] The sensing units 200f,g,h,i,j are communicatively coupled to a computing device 406, such as computing device 106 described above, for conveying output signals indicative of measured vibro-acoustic properties of the pipe network 402 (or from which these properties may be derived). A user interface 408 may also connected be to the computing device 406 for monitoring and/or visualizing the output signals received from the sensing units 200f,g,h,i,j. Visualization of the signals may be in the form of one or more graphs, diagrams, or other visual representation, and/or a visual indicator, such as an icon or other identifier indicative of a presence or absence, and/or an acquisition quality indicator of one or more of the output signals from the sensing units 200a,b,c, for visualizing the output signals or characteristics thereof. The processing of the output signals by the computing device 406 may be part of the system characterization of the pipe network 402. The characterized system may be visualized on the user interface 408. The characterized system may comprise information (e.g., characteristics) on various portions of the pipe network 402, e.g., the flow rate and the pressure in the pipe(s), the presence of defects, mineral buildups and/or leaks in the pipe network 402 and the like. In one embodiment, the user interface 408 may be a mobile device,

such as a tablet or smart phone. Other devices may be contemplated, such as a portable computer or a computer station.

[0066] The output signals received from the sensing units 200a,b,c may be computed so as to create, or at least rectify an analytical model of the elongated medium 102 and/or characterize a dynamic response of the elongated medium 102 to one or more input signals 112, as will now be further described. A method for analyzing vibro-acoustic properties of the elongated medium 102 or a pressurized fluid system including such elongated medium 102 will also be described.

[0067] An analytical model of the elongated medium 102 or the pressurized fluid system may first be computed. The analytical model (or "simulation") of the elongated medium 102 may assist in identifying what input signal(s) 112 should be generated to reveal information on the elongated medium 102. The analytical model may also be used to compare measured data or full system characterization as described below, with an expected dynamic behavior from the physics of the dynamic behavior of the elongated medium 102. In order to build the analytical model, information on the pressurized elongated medium 102 may be collected. Based on the collected information on the pressurized elongated medium, including mechanical properties of the elongated medium, the analytical model may be obtained. The analytical model may include the computation of various coefficients, and/or mechanical properties of the material of the elongated medium 102, such as the geometry, the tensile stress, the mass, the level of damping, the modulus of elasticity (E) (e.g., Young's modulus), a level of stiffness, the sound absorption coefficient, the thermal expansion coefficient, as some examples. In some cases where the elongated medium 102 is a prestressed concrete pipe, tensile stresses induced by steel wire may be taken into account in the analytical model. The analytical model may also include the computation of dimensions and account for the geometry (constant or variable) of the elongated medium 102. In at least some embodiments, the analytical model includes the computation of coefficients of fluids propagating inside and/or outside the elongated medium 102, e.g. density (ρ), specific heat, viscosity, modulus of compressibility (K), etc. A recognized mathematical model in the field of vibro-acoustics has been established by J. M. Muggleton, M. J. Brennan and R. J. Pinnington in the scientific publication entitled "Wavenumber Prediction of Waves in Buried Pipes for Water Leak Detection," published in the Journal of Sound and vibration (2002) 249(5), pages 939-954, the

content of which is incorporated herein for reference. This publication present the following equation derived from the equilibrium of forces relationship, which can be used to model the dynamic behavior of a cylindrical elongated medium:

$$1 - k_L^2 a^2 + v^2 \frac{k_S^2}{k_L^2 - k_S^2} = \frac{B_f a (1-v^2)}{Eh} \frac{k_f^2 a^2}{k_{fs}^2} \frac{J_0(k_{fs}^r a)}{J_0'(k_{fs}^r a)} - \frac{B_m a (1-v^2)}{Eh} \frac{k_d^2 a^2}{k_{ds}^2} \frac{H_0(k_{ds}^r a)}{H_0'(k_{ds}^r a)} - \frac{G_m a (1-v^2)}{Eh} \frac{k_r^2 a^2}{k_{rs}^2} \frac{H_0(k_{rs}^r a)}{H_0'(k_{rs}^r a)} \quad (1)$$

[0068] where k_L , k_S , k_f , k_{fs}^r , k_d , k_{ds}^r , k_r and k_{rs}^r are the compressional, shear, fluid, internal radial, external longitudinal, internal longitudinal, external shear and internal shear wavenumbers, respectively, v is the Poisson ratio, a is the radius, B_f and B_m are the bulk moduli of the internal and external media, respectively, G_m is the shear modulus of the external medium, E is the Young's modulus, h is the thickness of the wall and J_0, J_0' and H_0, H_0' are the Bessel functions and Hankel functions of order zero, respectively. Using eq. (1) it is possible to solve the mathematical model for at least two types of waves, namely $s=1$ and $s=2$, which correspond to a fluid dominated wave and an axial shell dominated wave, respectively.

[0069] For $s=1$ (equation (2)) and $s=2$ (equation (3)), the general equation (1) of the dynamic behavior of a cylindrical elongated medium becomes, respectively:

$$k_1^2 = k_f^2 \left(1 + \frac{\frac{2B_f}{a^2}}{\left(\frac{Eh}{a}\right) - \rho h \omega^2} \right) \quad (2)$$

$$k_2^2 = k_L^2 \left(1 + \frac{v^2 \frac{Eh}{a^2}}{1-v^2 \left(\frac{Eh}{a^2}\right) + \left(\frac{2B_f}{a}\right) - \rho h \omega^2} \right) \quad (3)$$

[0070] Where k_1 is the fluid dominated wave wavenumber, k_2 is the axial shell dominated wave wavenumber, ρ is the density of the shell material and ω is the angular frequency. In at least some embodiments, the compressional wavenumber k_L may be represented by the following equation:

$$k_L = \frac{\omega^2 \rho (1-v^2)}{E} \quad (4)$$

[0071] The fluid dominated wave ($s=1$) may generally propagate along a longitudinal axis of the elongated medium 102 and oscillates orthogonally to the longitudinal axis, and is thus sensitive to and highly dependent of the modulus of elasticity and Bulk modulus of the material it traverses, e.g., the fluid, the wall of the elongated medium 102 and the soil surrounding the elongated medium 102 when underground. The axial shell dominated wave ($s=2$) is usually confined within the wall of the elongated medium 102, and its propagation is typically less affected by or dependent on the modulus of elasticity and Bulk modulus of the fluid and the soil surrounding the elongated medium 102 when underground. As such, in at least some embodiments, the sensing unit 200 may measure at least one of the fluid dominated wave and the axial shell dominated wave, preferably both. It will be appreciated that both waves may coexist at the same time and have different speeds of propagation in the elongated medium 102. In such case, frequential separation may occur (e.g., through data processing, filters). In some cases, the separation between the frequency ranges may not be total, as overlaps can exist between the frequency ranges. Deconvolution algorithms can be used to separate the two waves from the measured signal if an overlap occurs. In other cases, the frequency ranges may not overlap, and the two waves can be extracted from the measured signal by either separating the signal in timeframes or filtering the signal in frequency.

[0072] The dynamic behavior of the elongated medium 102 may thereafter be modelled using properties inferred from the measured waves at input(s) and output(s) locations along the elongated medium 102. The modulus of elasticity, the Poisson ratio and/or the density of the wall of the elongated medium 102 may also be entered into the model to model the dynamic behavior of the elongated medium 102.

[0073] In some cases where the elongated medium 102 is a metallic pipe, in which case the modulus of elasticity of the pipe is substantially larger than the modulus of elasticity of the surrounding soil and of the fluid, the fluid dominated wave is generally predominant in the measured output signals. In such cases with metallic pipes, the fluid dominated wave can be measured in frequency bands ranging from 0 Hz to 3,000 Hz. Measurements of the fluid dominated wave in such situation can be made over large distances along the elongated medium 102 since the fluid dominated wave tends to attenuate less rapidly because of the high stiffness of such pipes. On the other hand, for metallic pipes, the axial shell dominated wave is rapidly attenuated by the pipe over a relatively short distance, and the presence of the

axial shell dominated wave in the measured signal may thus be less or not visible at the signal output locations along the elongated medium 102, unless signal output locations are very close from each others, such as a few meters away from each other (e.g., less than 10 meters). As such, the use of a fluid dominated wave for characterizing a metallic pipe may be preferable, according to the configuration of the pipe.

[0074] In other cases, the elongated medium 102 may be a plastic or polymer pipe, a plastic pipe network, or polymer pipe network which is generally less stiff than metal. As such, the fluid dominated wave, when propagating in plastic or polymer pipes, is more attenuated or “absorbed” by the pressurized fluid system compared to cases where the elongated medium is a metallic pipe. In addition, because of the dynamic properties of plastic or polymer pipes, including its lower modulus of elasticity and flexural modulus, the fluid dominated wave may be measurable on lower and narrower frequency bands, e.g., between 0 Hz and 200 Hz. The modulus of elasticity of the pipe may be similar to the modulus of elasticity of the soil. On the other hand, when propagating in plastic or polymer pipes, the axial shell dominated wave is able to propagate with less losses than the cases where the elongated medium 102 is a metallic pipe, because the dynamic properties of the wall of the plastic or polymer pipes cause less absorption (attenuation) of the axial shell dominated wave in such medium. As such, for plastic or polymer pipes, measuring axial shell dominated wave in the output signals can be achieved in relatively low frequency bands, e.g. between 200 Hz and 2,000 Hz compared to axial shell dominated wave in metallic pipes which would be seen at more than 3000 Hz. To summarize, depending on the nature of the elongated medium 102, the output signal may comprise different types of waves on a given set of frequency bands.

[0075] Yet, in other cases, where the elongated medium 102 is a prestressed concrete pressure pipe (PCCP) having a steel core cylinder with concrete layers inside and outside, the fluid dominated wave may reveal the overall pipe hoop stiffness of the layered pipe design, while the axial shell dominated wave may reveal structural information on the integrity of the steel core cylinder.

[0076] In practice, an input signal 112 may be injected in the elongated medium 102 and acoustic or vibro-acoustic resonance may be induced in response to the latter. This resonance may include harmonic vibrations that span in wide ranges of frequency bands and generate various types of waves. The resonance may, in at least some embodiments, generate fluid

dominated waves and the axial shell dominated waves. In other words, the amplification by vibro-acoustic resonance of various harmonics of the elongated medium 102 may generate various types of waves in the elongated medium 102, including fluid dominated waves and the axial shell dominated wave. The signal measured by the sensors generally comprises the input signal 112 and the generated resonance. Inducing more resonance, thus causing more signal amplification, by injecting an input signal 112 tuned based on the dynamic properties of the elongated medium may allow to extract more reliable information on the elongated medium 102. While a preferred excitation is one that may create vibro-acoustic resonance in the elongated medium 102 by targeting the structural natural frequencies of the elongated medium 102 for obtaining the dynamic response thereof, it will be appreciated that other types of excitations, such as excitation of modes of vibration not targeted towards the structural natural frequencies of the elongated medium 102, may be contemplated. It will be appreciated that the modes of vibration may vary, and be stationary or propagating, longitudinal and/or transverse and include fundamental modes and/or higher harmonics. In at least some embodiments, a single mode of vibration may be excited in the elongated medium 102, though more than one mode could also be.

[0077] In at least some embodiments, the parameters required for modelling the dynamic behavior of the elongated medium 102 are the modulus of elasticity, the density, the Poisson ratio, the wall thickness and the diameter thereof. As such, when the output signal comprises information related to the fluid dominated wave and the axial shell dominated wave, it is possible to generate an experimental model using a mathematical model including equations (2) and (3). Due to the physical nature of those waves, assumptions must be made in order to reduce the number of parameters to remain with a single unknown parameter. Generally, by assuming a theoretical value on the modulus of elasticity in the equation of the fluid dominated wave, and a theoretical value of the thickness of the pipe in the axial shell dominated wave, it is possible to model the dynamic behavior of the pipe and derive a stiffness profile of the pipe, using each equation independently. Stated otherwise, it may be possible to obtain the dynamic properties of the elongated medium 102 using only one of equations (2) and (3), using assumptions. Since assumptions are made on the properties of the wall of the elongated medium 102 instead of measurement of these characteristics, using only one of equations (2) and (3) may be limiting in terms of analytical accuracy. However, by combining both equations

(2) and (3) in a linear or non-linear system, it is possible to get rid of those assumptions and thereby obtain a dynamic behavior of the pipe that is not or quasi not based on theoretical values. As mentioned above, the proposed method requires a suited elongated medium 102, such as a plastic or polymer pipe, or metallic pipes with a smaller distance between the signal input location and signal output locations (or between adjacent signal output locations) in order to be able to adequately measure both fluid dominated and axial shell dominated waves. As such, the positioning of the sensors may be selected as a function of the mechanical properties of the elongated medium 102, such as its stiffness, or its sizes/dimensions.

[0078] In an embodiment, exciting the plastic or polymer pipe and sensing axial shell dominated wave and fluid dominated wave in the plastic or polymer pipe, and then solving the mathematical model based on equation (2) and equation (3) above may provide information on the stiffness and thickness of the pipe along its length that would otherwise not be possible to obtain by relying only on the fluid dominated wave and related signal data. It was found that for plastic or polymer pipes, since the axial shell dominated wave is within a lower frequency range than for metallic pipes, exciting the elongated medium 102 to induce resonance in such lower frequency range may produce sufficiently reliable data to characterize dynamically with sufficient precision hundreds of meters of plastic or polymer pipe based on a single input and multiple output characterization as described above.

[0079] Measuring both waves induced by the resonance or other types of induced vibrations in the elongated medium 102 may provide distinct sets of data which may be processed to obtain the characteristics of the fluid and the characteristics of the wall of the elongated medium 102. The sets of data may be combined (prior to or after they are processed). As part of the characterizing method, when generating the experimental model, the respective measured output signals may be normalized with the input signal in order to remove the input signal from the experimental model.

[0080] At least one or a plurality of wave generators 104 coupled with the elongated medium 102 may be used to generate a vibro-acoustic wave signal. The vibro-acoustic wave signal may be selected to excite the elongated medium 102 at least in an axial shell dominated wave frequency range. Such range can be known by analytical modelling and/or theoretical properties of the elongated medium 102, for example. In the plastic or polymer pipe(s) application, a vibro-acoustic wave signal may be generated, with such vibro-acoustic wave

signal being configured to induce resonance in the elongated medium 102 that will include the fluid dominated wave and the axial shell dominated wave. The first vibro-acoustic wave signal along with the induced resonance may be sensed by the sensing units 200 along the elongated medium 102 at the input location and respective output locations along the elongated medium 102. The acquired signal data may be stored in the sensing units 200 and/or computing device 106. By processing of such acquired signal data, the mathematical model defined by equation (2) and (3) described above may be solved. An experimental model of the elongated medium may be generated based on the solved mathematical model. Such experimental model may represent the dynamic behavior of the elongated medium 102. Such method for characterizing dynamically the elongated medium 102 may be repeated iteratively to compare the generated experimental models and verify their correlation. The correlation between successively generated experimental models may be used as a quality indicator of the input, output and experimental model obtained. In at least some embodiments, the vibro-acoustic wave signal generated by the wave generator(s) 104 may be subtracted from the signal sensed by the sensing units 200. In such case, the signal measured by the sensing units 200 may be representative of the response of the elongated medium 102 rather than to the excitation wave introduced in the elongated medium 102.

[0081] Once an experimental model has been generated as described above, it is possible to generate one or more additional experimental model by selecting a second input signal that is based on the quality indicator of the first experimental model, which can be established, e.g., by the signal to noise ratio of the measurements over the frequency bands, or correlation, as mentioned.

[0082] As such, another vibro-acoustic wave signal different from that generated in the first pass or first series of experimental model generation may be generated via the wave generator(s) 104 at the input location (same input location as the first vibro-acoustic wave signal) to induce resonance in the elongated medium 102. For example, such other vibro-acoustic wave signal may be selected to target resonance corresponding at least to the frequencies or frequency range of the fluid dominated wave signal and/or the axial shell dominated wave signal. The wave generator(s) 104 may then generate such other vibro-acoustic wave signal. The measurements of the signals made at the input location and at output locations along the elongated medium 102 may be processed to further generate

experimental model. Once the experimental model has been generated, it is possible to compare the experimental models derived from some or all of the vibro-acoustic wave signals generated and measured iteratively as mentioned above. This step can be used to further refine new input signals to be generated in the elongated medium 102, for example.

[0083] As part of the dynamic characterization method described herein above, the experimental model(s) may be plotted as a stiffness profile, which can include a normalization of the stiffness profile based on a nominal stiffness of the elongated medium 102. Such nominal stiffness may be based on an analytical model, as further described below. The plot can also include a visualization mean to identify a stiffness differential between the nominal stiffness and the stiffness profile.

[0084] In view of the foregoing, there is provided a method for characterizing dynamically the elongated medium 102. A first input signal is selected to excite the elongated medium 102 at least in an axial shell dominated wave frequency range. The first input signal is generated via a wave generator operatively coupled with the elongated medium 102. The first input signal is sensed at an input location and a first set of output signals is sensed at respective output locations along the elongated medium 102. The measured/sensed first set of output signals and the measured first input signal are processed, which includes solving a mathematical model. A first experimental model of the elongated medium 102 may then be generated based on the solved mathematical model. In at least some embodiments, the mathematical model is based on the combination of equations (2) and (3), as described above.

[0085] In at least some embodiments, the method may further include selecting a second input signal to excite the elongated medium 102 at least in one of an axial shell dominated wave frequency range, fluid dominated wave frequency range, or in a frequency range overlapping both of the axial shell and fluid dominated frequency ranges. The second input signal may be generated via the wave generator operatively coupled with the elongated medium 102. The second input signal may be measured at the input location and a second set of output signals may be measured at the respective output locations along the elongated medium 102. the measured second set of output signals and the measured second input signal may be processed, which includes solving the mathematical model (described above) another time. A second experimental model of the elongated medium 102 may then be generated based on the solved mathematical model. The selection of the second input signal

may be based on a quality indicator of the first experimental model. The method may also include comparing the experimental model obtained from the first input signal with that obtained from the second input signal. The comparison of the experimental models may be made by correlation, or cross-correlation, though other types of processing can be contemplated.

[0086] In at least some embodiments, the method may also include plotting the first experimental model as a stiffness profile of the elongated medium 102. The plotting of the experimental model as the stiffness profile may include normalizing the stiffness profile based on a nominal stiffness of the elongated medium 102. The nominal stiffness may be determined (provided as an assumption) based on an analytical model of the elongated medium 102.

[0087] In some cases, the method may also include conducting a modal analysis, by finite elements simulations or experimentally through measurements, as mentioned herein above, of the elongated medium 102 prior to selecting the first input signal. In such case, the selection of the first input signal may be based on a selected frequency range corresponding to an axial shell dominated wave frequency response of the elongated medium 102, a fluid dominated wave frequency response of the elongated medium 102, or a frequency range containing both responses .

[0088] In some cases, the plotting of the experimental model as the stiffness profile may include plotting a nominal stiffness of the elongated medium 102 to provide a visualization mean to identify a stiffness differential between the nominal stiffness and the stiffness profile along the elongated medium 102.

[0089] In at least some embodiments, the generating of the first experimental model may include normalizing the respective measured output signals with the first input signal.

[0090] In at least some embodiments, the comparing the first experimental model with the second experimental model may include cross-correlating the respective experimental models.

[0091] In at least some embodiments, plotting the experimental model(s) as a stiffness profile may be based on modelled modulus of elasticity, density, Poisson ratio, wall thickness and diameter of the elongated medium 102.

[0092] Other equations, or models, than those described above may be contemplated in order to characterize the elongated medium 102 and other methods can be used to generate the analytical model. In an embodiment, the analytical model may be generated, at least in part, using a finite element analysis (FEA) method and/or a boundary element analysis (BEA). In one embodiment, the model is generated using a Monte Carlo method. In at least some embodiments, the model is generated using artificial intelligence (AI) such as machine learning and/or deep learning techniques. Based on the analytical model, an estimated dynamic behavior of the pressurized elongated medium 102 or the pressurized fluid system may be characterized.

[0093] One or more test input signals may be created based on the estimated dynamic behavior and their capacity to reveal some aspects about the pressurized elongated medium 102. These one or more test input signals may be inputted into the pressurized fluid system via the wave generator, such as wave generator 104 described above. Output signals may then be measured at various locations along the pressurized fluid system. Such output signals are in reaction to the one or more test input signals propagating into the pressurized fluid system.

[0094] A full system characterization may be performed in terms of transmissibility from one output point to another (i.e., location of the sensing units or extraction point of the measured vibro-acoustic wave), cross-correlations (or any other comparison-type of processing) between output signals, cross-correlations (or any other comparison-type of processing) between an input signal and the respective output signals, transfer functions between the input signal and the respective output signals, or a combination thereof. In at least some embodiments, dynamic time warping, root-mean-square error, instantaneous phase synchrony, cross-spectral density, coherence and/or autocorrelation algorithms are performed to characterize the model.

[0095] In at least some embodiments, the dynamic behavior of the elongated medium may be discretized by time windowing the dynamic response. As such, the dynamic response is separated into a plurality of time windows, each being representative of an elongated portion of the elongated medium. In other words, the dynamic response provided in the spatial domain is transformed, using suited algorithm, e.g. Fourier transform functions, into the temporal domain and is thereafter discretized into a plurality of time windows. The duration of the time

windows is generally chosen so that the elongated portion has a length related to the wavelength of the vibro-acoustic wave. In some cases, the time windows may overlap. After being separated, a given frequency bandwidth of each time window may be averaged in order to obtain a dynamic response value, such as the root-mean-square (RMS) value or another value representative of a mean or average value over the time window, varying as a function of the position along the elongated member. Other algorithm suited for obtaining a frequency value representative of the dynamic behavior for each window may apply. It will be appreciated that the duration of the time window is representative of the spatial resolution of the dynamic response. The full characterization may provide measured vibro-acoustic properties of the pressurized fluid system, such as through processing or post-processing. Once a full characterization of the pressurized fluid system is computed, the expected dynamic behavior of the analytical model may be compared with the measured vibro-acoustic properties. Updated information about the pressurized fluid system may then be obtained.

[0096] Fig. 5 is a flow chart of an example of a method 500 for analyzing data for a system as system 100,300,400 described herein for characterizing an elongated medium, as elongated medium 102,302,402. The method 500 starts at step 502, where a vibro-acoustic wave signal is generated by a wave generator, such as wave generator 104,304,404 described above.

[0097] At step 504, a plurality of output signals (as defined hereinabove) are received. In at least some embodiments, geolocation data signals are also received. The plurality of output signals are extracted at selected locations along the elongated medium 102,302,402 using sensing units 200, as described above. It is understood that reference to sensing units 200 is meant to generally refer to the sensing units 200a,b,c,d,e,f,g,h,i,j described herein, for simplicity. The output signals may contain structural information on the elongated medium 102,302,402. Stated otherwise, structural information on the elongated medium 102, 302, 402 along an axial distance between adjacent ones of the sensing units 200 may be derived from the output signals. The geolocation data signals received at step 504 are indicative of a geolocation associated with respective ones of the selected locations of output points or sensing units 200. By knowing the geolocation of the selected locations, it is possible to obtain a geographical layout of the sensing units 200 distributed along the elongated medium 102,302,402.

[0098] At step 506, the plurality of output signals are processed. In at least some embodiments, the geolocation data signals are also processed. As such, transfer function characterization between the output signals of the plurality of sensing units 200 may be performed in order to characterize at least partially the elongated medium 102,302,402. In at least some embodiments, the system 100,300,400 is characterized by calculating a transmissibility (or transmissibility factor) between the plurality of output signals. Knowing the geolocation of each output signals and the difference in signal intensity or “signature” between each other, it is possible to compute the attenuation that a vibro-acoustic wave experiences when propagating in the elongated medium 102, 302,402 between the input point and the respective output points. It will be appreciated that this attenuation may correlate with structural properties of the elongated medium 102,302,402. The presence of defects, leaks, and/or mineral build-up on a surface of the elongated medium 102,302,402 between the sensing units 200 may modify the dynamic behavior of the elongated medium 102,302,402, hence the sound wave propagation therein. In at least some embodiments, as part of the processing, cross-correlation functions between respective ones of the output signals are used in order to identify similarities or differences between each other. Other comparison-type of processing between the different output signals may be contemplated as described above.

[0099] In at least some embodiments, cross-correlation functions between at least one of the output signals and a measured input signal at the input point of the vibro-acoustic wave generated by the wave generator 104,304,404 may be performed.

[00100] In at least some embodiments, a sensing unit 200 may be positioned serially with the wave generator 104,304,404, e.g., between the wave generator 104,304,404 and the input point in order to obtain a measurement of the vibro-acoustic wave at the input point. Such measurement may be computed as the actual input signal transmitted into the system to be characterized. In other embodiments, the wave generator 104,304,404 may include such a sensing unit, i.e., a sensing unit is built in the wave generator 104,304,404. The number of possible combinations of transfer functions between the plurality of output signals may be of $\frac{N!}{(N-2)!2!}$, where N is the number of sensing units 200 which probe the vibro-acoustic wave along the elongated medium 102,302,402. In other embodiments, the number of possible combinations of transfer functions between the plurality of output signals is N . It will be appreciated that various methods may apply to process the plurality of output signals and the

geolocation data signals, and that more than one output signals paired with a corresponding geolocation data signal is required to provide a full characterization of the elongated medium 102,302,402. In one exemplary embodiment, five sensing units 200 are used to characterize the elongated medium; a pair of sensing units on each side of the wave generator 104,304,404 and one near the input point. Such configuration may be suited to characterize the elongated medium 102,302,402 surrounding the input point.

[00101] Furthermore, at step 506, an experimental model of the elongated medium is generated based at least on the plurality of output signals and the geolocation data signals. In at least some embodiments, the structural properties extracted from the characterization of the elongated medium 102,302,402 may also be used to generate the experimental model. In at least some embodiments, an analytical model comprising estimated dynamic behavior of the elongated medium 102,302,402 is used to generate the experimental model.

[00102] At step 508, dynamic behavior of the elongated medium from the experimental model are computed. The dynamic behavior may include the stiffness of the elongated medium when subjugated to various conditions, from which structural information such as deformation, stress, brittleness, wall thickness and so on may be derived. The behavior of the fluid within the elongated medium 102,302,402 may affect the sound propagation. In at least some embodiments, the dynamic behavior includes the properties of the fluid, e.g. the pressure, velocity, temperature, density. The method 500 ends at step 510.

[00103] Fig. 6 is a flow chart of an example of a method 600 for rectifying an analytical model of an elongated medium based on an experimental characterization of the elongated medium. The method 600 starts at step 602.

[00104] At step 604, analytical properties of the elongated medium are received. The analytical model may be based on or compute various coefficients of the material of the elongated medium 102,302,402. Such analytical properties may be received via one or more analytical properties input made by an operator of the system 100,300,400. The analytical properties may also be stored in and/or called from a data library of a computing device such as computing device 106.

[00105] At step 606, the analytical model of the elongated medium is generated using the received analytical properties. Estimated dynamic behavior may be derived from the analytical

model of the elongated medium 102,302,402. In at least some embodiments, the analytical model, or an iteration thereof, may be obtained by acquisitioned vibro-acoustic measurements made on the elongated medium 102,302,402 using the system 100,300,400 described herein. In the method 600, the analytical model may serve as a reference model. Through iterative cycles, the analytical model may be refined using an experimental model of the elongated medium 102,302,402 as discussed with respect to method 500 described above. A refined iteration of the analytical model may thus be obtained, and may form a refined reference model upon which a subsequent iteration of the experimental model may at least partially be based, as further described below.

[00106] At step 608, a vibro-acoustic wave adapted to excite the elongated medium 102,302,402 is generated. The vibro-acoustic wave is defined at least by estimated tonal properties, which may be derived from the analytical model of the elongated medium 102,302,402. As such, the vibro-acoustic wave may be created so as to induce vibro-acoustic resonance in the elongated medium 102,302,402 by matching a plurality of natural frequencies of the elongated medium 102,302,402. In at least some embodiments, the vibro-acoustic wave contains a frequency signature including frequencies that will cause such resonance of at least portions of the elongated medium 102,302,402. In at least some embodiments, the vibro-acoustic wave may excite a plurality of harmonics of the natural frequencies of the elongated medium 102,302,402. Defects and/or leaks along the elongated medium 102,302,402 may affect the frequency signature of the elongated medium 102,302,402. In at least some embodiments, the vibro-acoustic wave is a pulsed signal having a short duration and a high amplitude. In other embodiments, the vibro-acoustic wave signal is a continuous signal.

[00107] At step 610, the generated vibro-acoustic wave is propagated in the elongated medium 102,302,402. The properties of the vibro-acoustic wave (e.g. the amplitudes and the frequencies, and energy) are generally selected so that the vibro-acoustic wave is able to travel at least to each sensing unit 200 without being overly or fully dampen due to attenuation.

[00108] At step 612, a plurality output signals extracted at selected locations along the elongated medium 102,302,402 are received. Furthermore, at step 612, geolocation data signals indicative of a geolocation associated with respective ones of the selected locations may optionally be received. The output signals may correspond to a modified (or "perturbated") version of the generated vibro-acoustic wave after being propagated in the elongated medium

102,302,402 from the input point to the out points. The plurality of output signals may comprise the input signal of the original vibro-acoustic wave with modified amplitudes, frequencies, and phases caused by signal attenuation and extrinsic perturbations. Such extrinsic perturbations may be caused at least by defects and/or leaks.

[00109] At step 614, the plurality of output signals, and the vibro-acoustic wave or transduction of said vibro-acoustic wave into an input signal are processed. In at least some embodiments, the geolocation data signals are also processed. Using the output signal of each sensing unit 200, whether or not with their respective geolocation, and the input signal, it is possible to compare the response at each sensing unit 200. Such comparison may contribute to the experimental modeling of a section of the elongated medium 102,302,402. The processing may include computing the transmissibility and/or cross-correlation between respective ones of the output signals in a number of possible permutations, and/or between the input signal and at least a respective one of the output signals. The processing may also include computing transfer functions between respective ones of the output signals and/or between the input signal and at least a respective one of the output signals. In at least some embodiments, the processing includes deconvoluting a plurality of such signals. Based on the processing described above, an experimental model of the elongated medium 102,302,402 is generated. The model may be generated according to step 506 presented above.

[00110] At step 616, dynamic behavior of the elongated medium 102,302,402 from the experimental model is computed. The dynamic behavior may be generated according to step 508 presented above. In a hypothetical scenario where a first iterative implementation of the method 600 would not provide the desired dynamic behavior and/or reveal the information sought on the elongated medium 102,302,402, for example because of an insufficient resolution of the acquisitioned output signals, steps 608-616 may be reprocessed using a different vibro-acoustic wave. The different vibro-acoustic wave may be arbitrary or be selected/built to provide a greater resolution of the dynamic behavior, such as a SVAI signal (described below), for instance.

[00111] At step 618, the analytical model is updated using the obtained dynamic behavior. Step 618 may be processed once the dynamic behavior match the predefined requirements. It will be understood that performing multiple iterations of the method 600 may lead to obtain a substantially refined analytical model. The method 600 ends at step 620.

[00112] Fig. 7 is a flow chart of an example of a method 700 for experimentally characterizing a pressurized fluid system in accordance with the above.

[00113] The method starts at step 702. At step 704, one or more test input signals are inputted, which may be referred to as specific vibro-acoustic input (SVAI) signals in the system at an input point.

[00114] At step 706, the SVAI signal at the input point is measured.

[00115] At step 708, output signals at respective first and at least second output points distanced from the input point and distanced from each other are measured. For sake of clarity, it is understood herein that the first output point herein is located at a closer distance from the input point than the at least second output point.

[00116] At step 710, a cross-correlation of the output signals is measured.

[00117] At step 712, a cross-correlation of each output signal with the measured SVAI signal is computed.

[00118] At step 714, transfer functions between each output signal and the measured SVAI signal are computed.

[00119] At step 716, a predictive transfer function of the system between the output signal at the second output point and the input point is computed. The computing of step 716 may be based on the transfer function between the output signal at the first output point and the SVAI signal.

[00120] At step 718, the predictive transfer function of the system is normalized. The normalization of step 718 may be performed with the transfer function between the output signal at the second output point and the SVAI signal. It will be appreciated that by generating transfer functions between output responses over input excitation, at step 718, it is possible to extrapolate (or predict) using non-linear functions the dynamic behavior of the elongated medium to virtual positions beyond regions characterized with comparison-type functions, such as the regions delimited between the input location and the output location(s). This aspect is particularly relevant to non-linear systems whose behavior cannot generally be extrapolated using conventional means, and so at least with acceptable accuracy. In some cases, the dynamic behavior of the elongated medium differs substantially between regions,

e.g. because of the presence of defects or repairs to the structure, and the behavior between two sensors modeled using transfer functions may not be applied to other regions. The predictive transfer function, on the other hand, may be used to predict the behavior of these regions by normalizing the transfer functions with the SVAI signal, which is considered to be similar along the elongated medium. In some cases, the predictive transfer function may be used to obtain the dynamic behavior of the elongated medium of regions near the wave generator(s). The method ends at step 720. The order of presentation of the computational steps is not intended to be limiting, as these steps could be performed in various permutations.

[00121] The method 700 may optionally include displaying the output signals on a user interface, such as by displaying one or more graphs or diagrams (e.g., spectrograms), and/or displaying a visual indication on the user interface in response to determining an acquisition quality indicator of the measured vibro-acoustic wave transduced into the output signals. In response to determining the acquisition quality indicator, the method 700 may further include triggering a request through the user interface to repeat an acquisition of the vibro-acoustic wave at the first output point and/or second output point. This step may ensure that the computing device receives reliable information and/or sufficient resolution on the vibro-acoustic wave measured at the first output point and/or second output point. The method 700 may optionally include displaying a cross-correlation spectrogram of the output signals on the user interface. The method 700 may optionally include displaying a cross-correlation spectrogram of at least one of the output signals and the SVAI signal on the user interface.

[00122] With reference to Fig. 8, part or all of the embodiments of the devices, systems and methods described herein may be implemented in a combination of both hardware and software.

[00123] Fig. 8 illustrates an example computing device 800 which may be used to implement the methods 500, 600 and/or 700 of Fig. 5, 6 and 7 respectively. The computing device 800 may correspond to the computing device 106 described above (or vice versa). The computing device 800 comprises a processing unit 802 and a memory 804 which has stored therein computer-executable instructions 806. The processing unit 802 may comprise any suitable devices configured to implement the functionality of the sensing system 100, 300, 400 and/or the methods 500, 600 and/or 700 such that instructions 806, when executed by the computing device 800 or other programmable apparatus, may cause the functions/acts/steps

performed by the sensing system 100,300,400 and/or the methods 500, 600 and/or 700 as described herein to be executed. The processing unit 802 may comprise, for example, any type of general-purpose microprocessor or microcontroller, a digital signal processing (DSP) processor, a central processing unit (CPU), an integrated circuit, a field programmable gate array (FPGA), a reconfigurable processor, other suitably programmed or programmable logic circuits, custom-designed analog and/or digital circuits, or any combination thereof.

[00124] The memory 804 may comprise any suitable known or other machine-readable storage medium. The memory 804 may comprise non-transitory computer readable storage medium, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. The memory 804 may include a suitable combination of any type of computer memory that is located either internally or externally to device, for example random-access memory (RAM), read-only memory (ROM), compact disc read-only memory (CDROM), electro-optical memory, magneto-optical memory, erasable programmable read-only memory (EPROM), and electrically-erasable programmable read-only memory (EEPROM), Ferroelectric RAM (FRAM) or the like. Memory 804 may comprise any storage means (e.g., devices) suitable for retrievably storing machine-readable instructions 806 executable by processing unit 802.

[00125] The computing device 800 may be any suitable computing device, such as a desktop computer, a laptop computer, a mainframe, a server, a distributed computing system, a portable computing device, a mobile phone, a tablet, or the like.

[00126] Figs. 9-12 show exemplary embodiments of vibro-acoustic properties profile obtained using the methods and systems presented herein. The vibro-acoustic properties profiles of Figs. 9-12 may thus represent dynamic behavior images of characterized pipes.

[00127] Fig. 9 shows the dynamic response of a pipe after being measured at six (6) different locations 900a,b,c,d,e,f using one or more sensors such as a sensor 202. As shown, the vibro-acoustic wave is induced at five (5) locations 902a,b,c,d,e using one or more wave generators such as a wave generator 104. Using the measurements, the dynamic properties of the pipe have been modelled and separated into five (5) sections 904a,b,c,d,e of the pipe. In each section 904a,b,c,d,e, the magnitude of the bottom portion of the profile is

representative of the dominant level of stiffness of the pipe. As such, a section having low magnitude at the bottom portion of the profile generally has a more desirable stiffness, while a section having high magnitude at the bottom portion of the profile generally has a less desirable stiffness. In the profile of Fig. 9, the sections 904a,b are sections that have been repaired using carbon fiber, which causes an increase in stiffness. The sections 904c,d,e have not been repaired, which is reflected by a less desirable stiffness as shown in the profile of Fig. 9.

[00128] Fig. 10 shows another exemplary dynamic response profile of a pipe. The profile of Fig. 10 includes 5 sections 1000a,b,c,d,e; three (3) larger sections 1000a,c,e corresponding to segments of pipes and two (2) smaller sections 1000b,d in which vibro-acoustic waves are introduced in the pipe in order to induce the dynamic response. As shown the sections 1000b,d do not comprise vibro-acoustic properties, because the measurements taken at these regions are mainly the introduced vibro-acoustic waves themselves, which mask the dynamic response of the pipe. In some cases where more than one wave generator is installed on a pipe, it is possible to obtain the vibro-acoustic properties profile of the regions near the wave generator by alternating the generator in operation. In the profile shown in Fig. 10, the dark spots in the high magnitude portion at the bottom of the profile are representative of distressed areas in the stiffness profile of the pipe corresponding to known wire breaks.

[00129] Fig. 11 is a profile including a dynamic response curve 1100a representing the vibro-acoustic energy variation (VAEV) of the dynamic response as a function of position in a pipe. In this exemplary profile, the VAEV may be obtained using cross-correlation functions between outputs for specific frequency bands. It will be appreciated that the VAEV distribution may be obtained by time windowing the dynamic behavior of the pipe and by averaging the frequency of each time window. It will be appreciated that the VAEV measured level increases with the number of defects in the portions of the pipe. The masked regions 1100b,c are regions where vibro-acoustic waves have been introduced to induce the dynamic response of the pipe.

[00130] Fig. 12 shows a stiffness profile of the pipe. The stiffness profile has four regions 1200a,b,c,d corresponding that can each be graded to a level of condition of the pipe. For instance, regions 1200a,d correspond to a desirable level of condition of the pipes as they have a high stiffness, region 1200b corresponds to an undesirable level of condition of the pipe because of the low stiffness and region 1200c corresponds to a more desirable level of

condition of the pipe because of the very high stiffness. Also, the defects may be detected in the stiffness profile, as they correspond to regions of relatively low stiffness.

[00131] In at least some embodiments, the vibro-acoustic properties profile shown in Figs. 9-12 may be displayed on a processing device of a worker making inspections on the pipe. In this case, the worker is able to identify sections of the pipe that need repair without using an invasive means of inspection.

[00132] In view of the various aspects described above, a method for characterizing a dynamic behavior of an elongated medium will now be described. The method includes generating an input wave signal at an input location along the elongated medium, the input wave signal including a vibro-acoustic wave signal and being selected to excite at least a mode of vibration in the elongated medium. As described above, the generated input wave signal is configured to excite the elongated medium to induce vibrations therein. The mode of vibration may include components such as the modal frequency, which represents the frequency at which the vibration occurs, and the mode shape, which represents the pattern of displacement of the vibration. The component may also include the phase of the vibration and the amplitude thereof.

[00133] The method also includes measuring a first output wave signal at a first location along the elongated medium spaced apart from the input location, and generating a first electrical signal based thereof, the first electrical signal indicative of a first component of the first output wave signal and measuring a second output wave signal at a second location along the elongated medium spaced apart from the input location and from the first location, and generating a second electrical signal based thereof, the second electrical signal indicative of a second component of the second output wave signal. As described above, the output wave signals may be measured by a suited sensor, such as an accelerometer or a piezoelectric transducer described with respect to Figs. 1 and 2. The sensor may be configured for transducing the mechanical vibrations of the output wave signals into an electrical signal, which is thereafter provided to a processing device. The vibrations measured at the sensor may be acoustic or vibro-acoustic, depending on the embodiment. It will be understood that the computing processes of the method is performed using the electrical signals generated at the sensors.

[00134] The method also includes comparing the first and second components of the mode of vibration to one another based on the first and second electrical signals and computing a dynamic response of the elongated medium based on said comparing.

[00135] In at least some embodiments, the input wave signal is selected to target a structural natural frequency of the elongated medium to induce a resonance on a predefined frequency band. While various modes of vibrations may be excited using the generated input signal, in this embodiment, the input signal is configured to create resonance in the elongated medium, which may increase the amplitude of the output signal.

[00136] In at least some embodiments, the method further includes measuring the input wave signal at the input location and generating a third electrical signal based thereof, the third electrical signal indicative of a third component of the input wave signal, wherein said comparing further includes comparing the third component of the mode of vibration on the third electrical signal with the first and second components of the mode of vibration on the first and second electrical signals. In some cases, the input wave signal is measured closed to a wave generator using a suited sensor, as described further above. It will be appreciated that the first, second and third electrical signals are representative of wave signals measured at the first and second locations and at the input location, respectively.

[00137] In at least some embodiments, the method further includes obtaining an analytical model of the elongated medium including at least estimated tonal properties of the elongated medium, wherein the input wave signal is defined by the estimated tonal properties.

[00138] In at least some embodiments, the method further includes generating an experimental model of the elongated medium based on the first and second signals, and updating the analytical model based on the experimental model, wherein said computing the dynamic response is performed using the analytical model and/or the experimental model.

[00139] In at least some embodiments, the method further includes associating a quality indicator with the generated experimental model, the quality indicator including a given value of a signal to noise ratio, a presence of an input signal in the measured output signals, and/or a given value of coherence between output signals.

[00140] In at least some embodiments, said generating the experimental model comprises conducting a modal analysis of the elongated medium and using the modal analysis in said obtaining the analytical model.

[00141] In at least some embodiments, conducting the modal analysis includes predicting, using non-linear functions, a dynamic behavior of the elongated medium at virtual positions beyond regions delimited between the input location and the first and second locations.

[00142] In at least some embodiments, the method further includes dividing the dynamic response into a plurality of time windows and obtaining a dynamic response of the elongated medium for each one of the plurality of time windows.

[00143] In at least some embodiments, said obtaining the dynamic response for each one of the plurality of time windows includes calculating a signal average over a given frequency bandwidth.

[00144] In at least some embodiments, said comparing includes computing a cross-correlation of the first and second electrical signals, computing a cross-correlation of the first and second electrical signals with the third electrical signal, computing transfer functions between the first and second electrical signals and the third electrical signal, and/or computing a predictive transfer function of the elongated medium between the first and second electrical signals based on the computed transfer functions.

[00145] In at least some embodiments, said comparing includes normalizing the predictive transfer function of the elongated medium with the computed transfer functions.

[00146] In at least some embodiments, the method further includes displaying the first and second output wave signals on a user interface and/or displaying a visual indication on the user interface in response to determining an acquisition quality indicator of the measured first and second output wave signals.

[00147] In at least some embodiments, said generating the input signal includes generating a set of tones, the set of tones being sequentially selected in frequency or in a predefined pattern.

[00148] In at least some embodiments, said generating the wave signal includes selecting a first input wave signal to excite the elongated medium in an axial shell dominated wave frequency range and/or a fluid dominated wave frequency range.

[00149] In at least some embodiments, said computing the dynamic response is performed solving a mathematical model including the following equations:

$$k_1^2 = k_f^2 \left(1 + \frac{\frac{2B_f}{a}}{\left(\frac{Eh}{a^2}\right) - \rho h \omega^2} \right)$$

$$k_2^2 = k_L^2 \left(1 + \frac{v^2}{1 - v^2} \frac{\frac{Eh}{a^2}}{\left(\frac{Eh}{a^2}\right) + \left(\frac{2B_f}{a}\right) - \rho h \omega^2} \right)$$

[00150] where k_L , k_f , k_1 k_2 are the compressional, fluid, fluid dominated wave and axial shell dominated wave wavenumbers, respectively, v is the Poisson ratio of the elongated medium, a is the radius of the elongated medium, B_f is the bulk modulus of external media, E is the Young's modulus of the elongated medium, h is a wall thickness, ρ is the density of the shell material and ω is the angular frequency.

[00151] In at least some embodiments, the method further includes plotting a stiffness profile of the elongated medium, wherein said plotting includes normalizing the stiffness profile based on a nominal stiffness of the elongated medium, plotting the normalized stiffness profile of the elongated medium to provide a visualization mean to identify a stiffness differential between the nominal stiffness and the stiffness profile along the elongated medium and/or plotting the Young's modulus, the density, the Poisson ratio, the wall thickness and/or a diameter of the elongated medium. In at least some embodiments, the nominal stiffness may be determined based on the analytical model of the elongated medium. It will be appreciated that the diameter (or other cross-sectional dimension) of the elongated medium may be obtained from a structural plan of the elongated medium, may be obtained from the analytical model, or may be measured by an operator or any suited autonomous device.

[00152] In at least some embodiments, said computing includes subtracting the third electrical signal from first and second electrical signals.

[00153] In at least some embodiments, the first component of the first output wave signal and/or the second component of the second output wave signal include a modal frequency.

[00154] In view of the various aspects described above, a system for characterizing an elongated medium will now be described. The system includes a wave generator configured for generating a vibro-acoustic wave and, the vibro-acoustic wave being selected to excite a mode of vibration (e.g., one or more modes) in the elongated medium, a plurality of sensing units attached to the elongated medium at different locations and a computing device. Each sensing unit has a sensor for detecting and measuring an output wave signal at an output location along the elongated medium and a processing unit for transducing the measured output wave signal into an electrical signal. The computing device is communicatively coupled to the plurality of sensing units, the computing device having a processing unit and a memory having stored thereon program instructions executable by the processing unit for receiving the electrical signal of each one of the plurality of sensing units, the output wave signals including the excited mode of vibration, generating an analytical model of the elongated medium and computing a dynamic behavior of the elongated medium by comparing the analytical model with the electrical signal of each one of the plurality of sensing units. It will be appreciated that the system of the current embodiment may correspond to the system 100, 300, 400 described above.

[00155] In at least some embodiments, each sensing unit further includes a geolocation identifier for identifying a geolocation of the sensing unit, and wherein the program instructions further include receiving the geolocation of each sensing unit via the geolocation identifier and computing the dynamic behavior using the geolocation of each sensing unit.

[00156] In view of the various aspects described above, a system for characterizing an elongated medium will now be described. The system includes a wave generator configured for generating a vibro-acoustic wave in the elongated medium, a plurality of sensing units attached to the elongated medium at different locations and a computing device communicatively coupled to the plurality of sensing units. Each sensing unit has a geolocation identifier for identifying the geolocation of the sensing unit, a sensor for detecting and measuring the vibro-acoustic wave at an output point along the elongated medium and a processing unit for transducing the measured vibro-acoustic wave into an output signal. The computing device has a processing unit and a memory having stored thereon program

instructions executable by the processing unit for receiving the output signal of each one of the plurality of sensing units and the geolocation thereof, generating an analytical model of the elongated medium and computing a dynamic behavior of the elongated medium by comparing the analytical model with the measured output signals and the geolocation thereof. It will be appreciated that the system of the current embodiment may correspond to the system 100, 300, 400 described above.

[00157] In view of the various aspects described above, a method for experimentally characterizing a pressurized fluid system will now be described. The method comprises inputting one or more test input signals at an input point, the one or more test input signals having a duration at least longer than a period needed to propagate across the pressurized fluid system; measuring output signals from a respective first and at least second output points distanced from the input point; computing a cross-correlation of the output signals, thereby obtaining a dynamic response of the pressurized fluid system; dividing the dynamic response into a plurality of time windows; and obtaining a dynamic response of the pressurized fluid system for each of time windows.

[00158] In view of the various aspects described above, a method for analyzing data for a system for characterizing an elongated medium will now be described. The method comprises receiving a measured input signal from an input location along the elongated medium; receiving a plurality of output signals from selected locations distanced from the input location along the elongated medium; processing the plurality of output signals, and generating an experimental model of the elongated medium based at least on the plurality of output signals and the input signal; and computing a dynamic behavior of the elongated medium from the experimental model.

[00159] In view of the various aspects described above, a method for rectifying an analytical model for characterizing an elongated medium will now be described. The method comprises receiving analytical properties of the elongated medium; generating an analytical model of the elongated medium using the analytical properties thereof, the analytical model including at least estimated tonal properties of the elongated medium; generating a vibro-acoustic wave adapted to excite the elongated medium, the vibro-acoustic wave defined at least by the estimated tonal properties of the analytical model of the elongated medium; propagating the generated vibro-acoustic wave in the elongated medium; receiving a plurality of output signals

extracted at selected locations along the elongated medium; processing the plurality of output signals and a measured input signal of the vibro-acoustic wave from an input location, and generating an experimental model of the elongated medium based on the plurality of output signals and the measured input signal; computing a dynamic behavior of the elongated medium from the experimental model; and updating the analytical model using the computed dynamic behavior.

[00160] In view of the various aspects described above, a method for experimentally characterizing a pressurized fluid system. The method comprises inputting one or more test input signals at an input point; measuring the one or more test input signals from the input point; measuring output signals from a respective first and at least second output points distanced from the input point; computing a cross-correlation of the output signals; computing a cross-correlation of each output signal with the measured one or more test input signals; computing transfer functions between each output signal and the measured one or more test input signals; computing a predictive transfer function of the pressurized fluid system between the output signal at the second output point and the output signal at the first output point based on the transfer function between the output signal at the first output point and the one or more test input signals; and normalizing the predictive transfer function of the pressurized fluid system with the transfer function between the output signal at the second output point and the one or more test input signals.

[00161] In view of the various aspects described above, a method for characterizing dynamically an elongated medium will now be described. The method comprises selecting a first input signal to excite the elongated medium at least in an axial shell dominated wave frequency range, generating the first input signal via a wave generator operatively coupled with the elongated medium, sensing the first input signal at an input location and a first set of output signals at respective output locations along the elongated medium, processing the measured first set of output signals and the measured first input signal, including solving a mathematical model; and generating a first experimental model of the elongated medium based on the solved mathematical model.

[00162] The term "communicatively connected" or "communicatively coupled to" may include both direct communicative coupling (in which two elements that are communicatively coupled to each other communicates together without interfacing components) and indirect

communicative coupling (in which at least one additional element communicatively interfaces with the two elements). For instance, the term "communicatively connected" or "communicatively coupled to" may include a wireless connection over a communication network such as the Internet or 5G network.

[00163] As can be understood, the examples described above and illustrated are intended to be exemplary only. The scope is indicated by the appended claims. While the embodiments presented herein generally relate to a pressurized fluid system, it will be understood that the technology is not bound to characterization of a pressurized fluid system as various other fields may apply, e.g., the characterisation of railways, bridges, wind turbines, cables, buildings, platforms and any other types of structures subject to stress that may induce defects and which may acoustically or vibro-acoustically be excited using methods and systems such as those described herein.

WHAT IS CLAIMED IS:

1. A method for characterizing a dynamic behavior of an elongated medium, the method comprising:

generating an input wave signal at an input location along the elongated medium, the input wave signal including a vibro-acoustic wave signal and being selected to excite a mode of vibration in the elongated medium;

measuring a first output wave signal at a first location along the elongated medium spaced apart from the input location, and generating a first electrical signal based thereof, the first electrical signal indicative of a first component of the first output wave signal;

measuring a second output wave signal at a second location along the elongated medium spaced apart from the input location and from the first location, and generating a second electrical signal based thereof, the second electrical signal indicative of a second component of the second output wave signal;

comparing the first and second components of the mode of vibration to one another based on the first and second electrical signals; and

computing a dynamic response of the elongated medium based on said comparing.

2. The method of claim 1, wherein the input wave signal is selected to target a structural natural frequency of the elongated medium to induce a resonance on a predefined frequency band.

3. The method of claim 1 or 2, further comprising measuring the input wave signal at the input location and generating a third electrical signal based thereof, the third electrical signal indicative of a third component of the input wave signal, wherein said comparing further includes comparing the third component of the input wave signal on the third electrical signal with the first and second components of the first and second output wave signals on the first and second electrical signals.

4. The method of any one of claims 1 to 3, further comprising obtaining an analytical model of the elongated medium including at least estimated tonal properties of the elongated medium, wherein the input wave signal is defined by the estimated tonal properties.

5. The method of claim 4, further comprising:

generating an experimental model of the elongated medium based on the first and second signals; and

updating the analytical model based on the experimental model,

wherein said computing the dynamic response is performed using the analytical model and/or the experimental model.

6. The method of claim 5, further comprising associating a quality indicator with the generated experimental model, the quality indicator including a given value of a signal to noise ratio, a presence of an input signal in the measured output signals, and/or a given value of coherence between output signals.

7. The method of any one of claims 4 to 6, wherein said generating the experimental model comprises conducting a modal analysis of the elongated medium and using the modal analysis in said obtaining the analytical model.

8. The method of claim 7, wherein conducting the modal analysis includes predicting, using non-linear functions, a dynamic behavior of the elongated medium at virtual positions beyond regions delimited between the input location and the first and second locations.

9. The method of any one of claims 1 to 8, further comprising:

dividing the dynamic response into a plurality of time windows; and

obtaining a dynamic response of the elongated medium for each one of the plurality of time windows.

10. The method of claim 9, wherein said obtaining the dynamic response for each one of the plurality of time windows includes calculating a signal average over a given frequency bandwidth.

11. The method of any one of claims 3, wherein said comparing includes:

computing a cross-correlation of the first and second electrical signals;

computing a cross-correlation of the first and second electrical signals with the third electrical signal;

computing transfer functions between the first and second electrical signals and the third electrical signal; and/or

computing a predictive transfer function of the elongated medium between the first and second electrical signals based on the computed transfer functions.

12. The method of claim 11, wherein said comparing includes normalizing the predictive transfer function of the elongated medium with the computed transfer functions.

13. The method of claim 11 or 12, further comprising displaying the first and second output wave signals on a user interface, and/or displaying a visual indication on the user interface in response to determining an acquisition quality indicator of the measured first and second output wave signals.

14. The method of any one of claims 1 to 13, wherein said generating the input signal includes generating a set of tones, the set of tones being sequentially selected in frequency or in a predefined pattern.

15. The method of any one of claims 1 to 14, wherein said generating the input wave signal includes selecting a first input wave signal to excite the elongated medium in an axial shell dominated wave frequency range and/or a fluid dominated wave frequency range.

16. The method of claim 15, wherein said computing the dynamic response is performed solving a mathematical model including the following equations:

$$k_1^2 = k_f^2 \left(1 + \frac{\frac{2B_f}{a}}{\left(\frac{Eh}{a^2}\right) - \rho h \omega^2} \right)$$

$$k_2^2 = k_L^2 \left(1 + \frac{v^2}{1 - v^2} \frac{\frac{Eh}{a^2}}{\left(\frac{Eh}{a^2}\right) + \left(\frac{2B_f}{a}\right) - \rho h \omega^2} \right)$$

where k_L , k_f , k_1 k_2 are the compressional, fluid, fluid dominated wave and axial shell dominated wave wavenumbers, respectively, v is the Poisson ratio of the elongated medium, a is the radius of the elongated medium, B_f is the bulk modulus of external media, E is the Young's modulus of the elongated medium, h is a wall thickness, ρ is the density of the shell material and ω is the angular frequency.

17. The method of claim 16, further comprising plotting a stiffness profile of the elongated medium, wherein said plotting includes:

normalizing the stiffness profile based on a nominal stiffness of the elongated medium;

plotting the normalized stiffness profile of the elongated medium to provide a visualization mean to identify a stiffness differential between the nominal stiffness and the stiffness profile along the elongated medium; and/or

plotting the Young's modulus, the density, the Poisson ratio, the wall thickness and/or a diameter of the elongated medium.

18. The method of claim 3, wherein said computing includes subtracting the third electrical signal from first and second electrical signals.

19. The method of any one of claims 1 to 18, wherein the first component of the first output wave signal and/or the second component of the second output wave signal each include a modal frequency.

20. A system for characterizing an elongated medium, the system comprising:

a wave generator configured for generating a vibro-acoustic wave, the vibro-acoustic wave being selected to excite a mode of vibration in the elongated medium;

a plurality of sensing units attached to the elongated medium at different locations, each sensing unit having:

a sensor for detecting and measuring an output wave signal at an output location along the elongated medium, and

a processing unit for transducing the measured output wave signal into an electrical signal; and

a computing device communicatively coupled to the plurality of sensing units, the computing device having a processing unit and a memory having stored thereon program instructions executable by the processing unit for:

receiving the electrical signal of each one of the plurality of sensing units, the output wave signals including the excited mode of vibration;

generating an analytical model of the elongated medium; and

computing a dynamic behavior of the elongated medium by comparing the analytical model with the electrical signal of each one of the plurality of sensing units.

21. The system of claim 20, wherein each sensing unit further includes a geolocation identifier for identifying a geolocation of the sensing unit, and wherein the program instructions further include:

receiving the geolocation of each sensing unit via the geolocation identifier; and

computing the dynamic behavior using the geolocation of each sensing unit.