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Chiara DARIAO, *et al.*
Sound Bullets

http://www.telegraph.co.uk/health/healthnews/7556854/Sound-bullets-latest-weapon-against-cancer.html
6 Apr 2010

Sound bullets latest weapon against cancer

A machine that fires powerful "sound bullets" made from concentrated noise could be used to treat cancer, say scientists

Two researchers have devised a prototype "acoustic lens" that focuses sound into high-energy pulses.

A "sonic scalpel" based on the device could target and destroy tumours, it is claimed.

Other potential uses include medical imaging and testing materials - and the scientists also hint at possible military applications.

The machine consists of an array of 441 small steel spheres arranged in 21 parallel chains.

Squeezing the spheres together by varying amounts affects the speed at which sound travels through the chains. This is because sound moves faster through solid objects than through air.

By carefully adjusting the speed of sound passing through different chains, the acoustic lens can be "tuned" to emit sound waves that overlap and amplify one another at a specific focal point. The result is a high-energy compact pulse of sound vibrations.

Dr Allessandro Spadoni and Dr Chiara Daraio, both from the California Institute of Technology in Pasadena, US, described their invention today in the journal Proceedings of the National Academy of Sciences.

They wrote: "The acoustic energy in the host medium is focused into 'sound bullet' - a travelling, compact region of high energy density.

"Sound bullets result from the coalescence of acoustic waves, which have frequencies in the audible range for the lens parameters we chose."

The device allowed the "generation of compact sound bullets of very large amplitudes", said the scientists.

They added: "Acoustic lenses like the one we demonstrated have the potential to dramatically impact a variety of applications, such as biomedical devices, non-destructive evaluation and defence systems.

"For example, sound bullets may conceivably be used as a non-invasive scalpel to accurately target tumours in hyperthermia (heat treatment) applications."

METHOD AND SYSTEM FOR FORMATION OF HIGHLY NONLINEAR PULSES
US2009229910
WO2009100061

Inventor(s): DARAIO CHIARA
Classification: - international: G10K15/04; G10K15/04 - European: G10K15/00

Abstract -- A method and system supporting the formation and propagation of tunable highly nonlinear pulses

using granular chains composed of non-spherical granular systems. Such a method and system may be used to support the creation of tunable acoustic band gaps in granular crystals formed of particles with different geometries (spherical or not) in which the tunability is achieved by varying the static precompression, type of excitation and/or pulse amplitude in the system.

Description

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]The present application is related to and claims the benefit of the following copending and commonly assigned U.S. Patent Applications: U.S. Patent Application No. 61/063,903, titled "Method and device for actuating and sensing highly nonlinear solitary waves in surfaces, structures and materials," filed on Feb. 7, 2008; U.S. Patent Application No. 61/067,250, titled "System Supporting the Formation and Propagation of Tunable Highly Nonlinear Pulses, Based on Granular Chains Composed of Particles with Non Spherical Geometry," filed on Feb. 27, 2008; U.S. Patent Application No. 61/124,920, titled "Method and Apparatus for Nondestructive Evaluations and Structural Health Monitoring of Materials and Structures," filed on Apr. 21, 2008; and U.S. patent application Ser. No. 12/251,164, "Method and Apparatus for Nondestructive Evaluation and Monitoring of Materials and Structures," filed on Oct. 14, 2008; whereby the entire contents of these applications are incorporated herein by reference.

BACKGROUND

[0002]1. Field

[0003]This disclosure relates to a method and system for the formation and propagation of highly nonlinear pulses with selectable pulse properties. More particularly, the present disclosure describes the generation and propagation of pulses through the use of granular chains consisting of particles with desirable geometries.

[0004]2. Description of Related Art

[0005]The existence of the highly nonlinear regime of wave propagation in solids was discovered while studying the shock absorption properties of granular matter. The model typically used to represent the simplest form of granular systems consisted of a one dimensional (1-D) chain of spherical beads regulated by Hertzian contact interaction potentials. However, a new, general wave dynamic theory, supporting compact solitary waves, was derived for all structured homogeneous materials showing a highly nonlinear force (F)-displacement (.delta.) response dictated by the intrinsically nonlinear potential of interaction between its fundamental components. This general nonlinear spring-type contact relation can be expressed as shown below in Eq. (1):

F.apprxeq.A.delta..sup.n Eq.(1)

where A is a material's parameter and n is the nonlinear exponent of the fundamental components' contact interaction (with n>1). For Hertzian systems, such as those consisting of a chain of spherical beads, the n exponent of interaction is equal to 1.5.

[0006]Within the present disclosure, "granular matter" is defined as an aggregate of "particles" in elastic contact with each other, preferably in linear or network shaped arrangements. In addition to the nonlinear contact interaction present in such systems, and related purely to the particle's geometry, another unusual feature of the granular state is provided by the zero tensile strength, which introduces an additional nonlinearity (asymmetric potential) to the overall response. In the absence of static precompression acting on the systems, these properties result in a negligible linear range of the interaction forces between neighboring particles leading to a material with a characteristic sound speed equal to zero in its uncompressed state (c.sub.0=0): this has led to the introduction of the concept of "sonic vacuum". This makes the linear and weakly nonlinear continuum approaches based on Korteveg-de Vries (KdV) equation invalid and places granular materials in a special class according to their wave dynamics. This highly nonlinear wave theory supports, in particular, a new type of compact highly tunable solitary waves that have been experimentally and numerically observed in several works for the case of 1-D Hertzian granular systems.

SUMMARY

[0007]Embodiments of the present invention described herein include a method and system supporting the formation and propagation of tunable highly nonlinear pulses using granular chains composed of non-spherical granular systems and a linearized version thereof supporting the formation of tunable acoustic band gaps. Other embodiments of the present invention include a method and system to support the creation of tunable acoustic band gaps in granular crystals formed of particles with different geometries (spherical or not) in which the tunability is achieved by varying the static precompression, type of excitation and/or pulse amplitude in the system.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0008] **FIG. 1** shows a photograph of stainless steel elliptical particles.

FIG. 1

[0009] **FIG. 2A** shows an experimental set up of a vertically stacked chain of stainless steel elliptical beads.

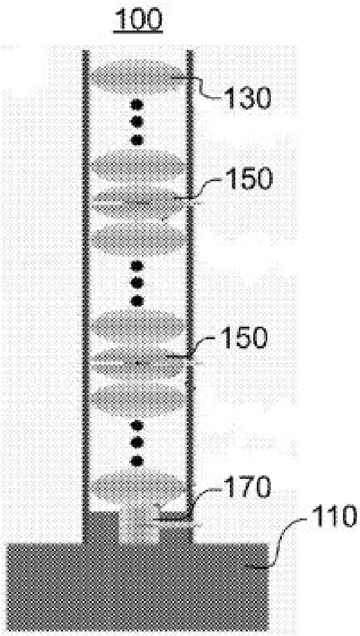


FIG. 2A

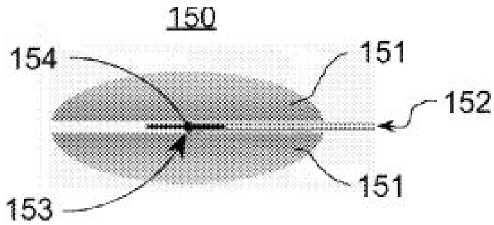


FIG. 2B

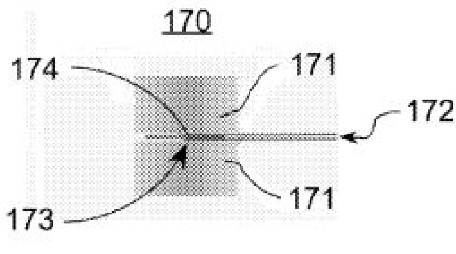


FIG. 2C

[0010] **FIG. 2B** shows a sensor particle having an encapsulated piezo-sensor.

[0011] **FIG. 2C** shows a wall sensor having an encapsulated piezo-sensor.

[0012] **FIG. 3** shows the formation of solitary waves excited by impact in a chain of stainless steel elliptical beads.

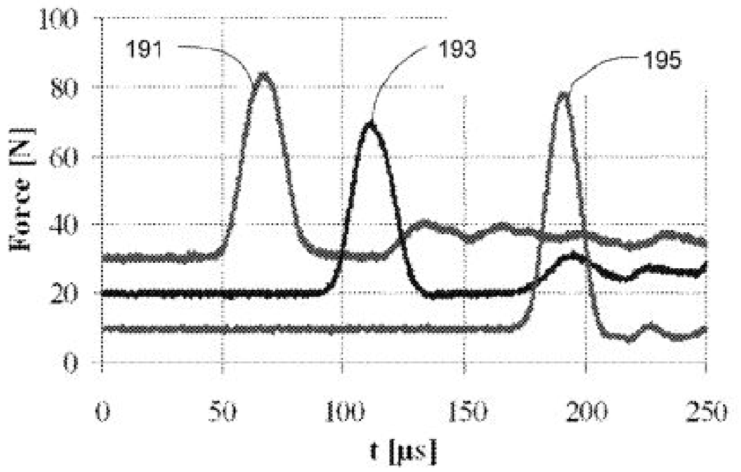


FIG. 3

[0013] **FIGS. 4A and 4B** illustrate relative orientations of a pair of cylindrical particles.

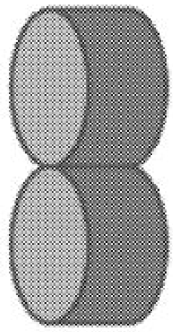


FIG. 4A

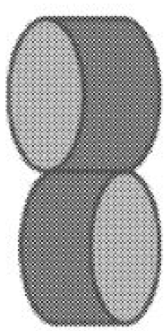


FIG. 4B

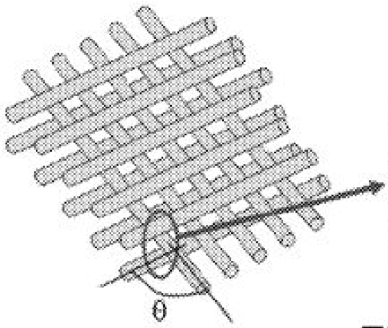


FIG. 4C

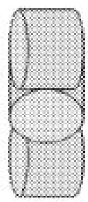
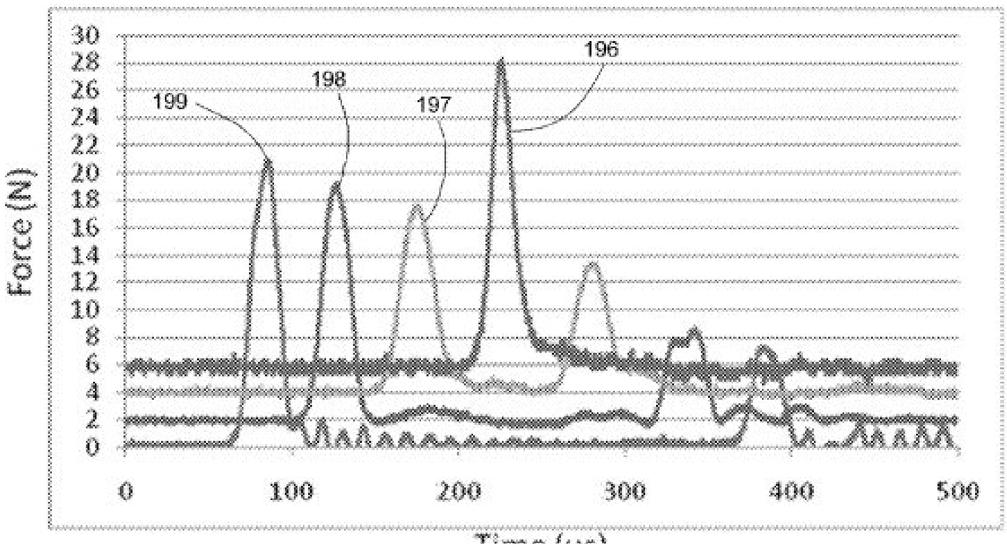


FIG. 4D

[0014] **FIG. 4C** shows a schematic diagram of a 3-D system assembled from an array of cylindrical contacts.

[0015] **FIG. 4D** illustrates the vertical alignment of the cylindrical contacts in FIG. 4C.

[0016] **FIG. 5** shows experimental data obtained from a vertically aligned chain of cylinders oriented perpendicular to each other.



Time (μs)

FIG. 5

[0017] **FIG. 6** shows a schematic diagram of a rod-based 3-D system 200 using precompression.

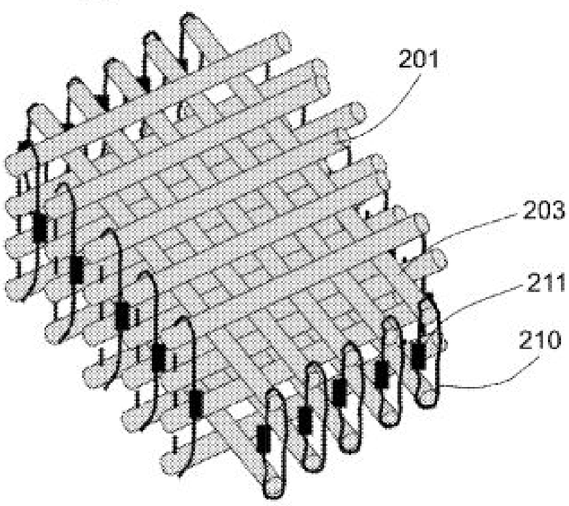


FIG. 6

[0018] **FIG. 7A** shows a system in which one dimensional chains of particles are held to each other at weld points.

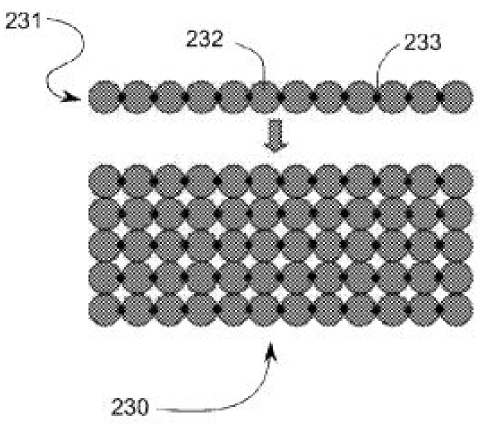


FIG. 7A

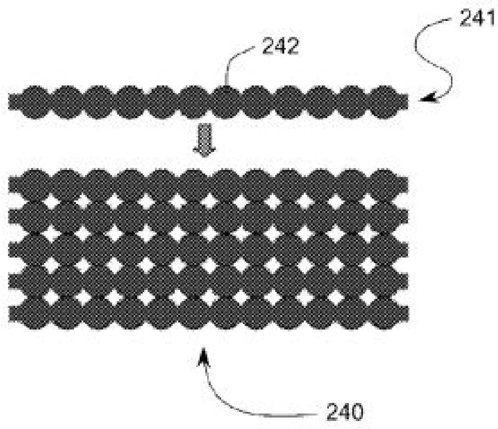
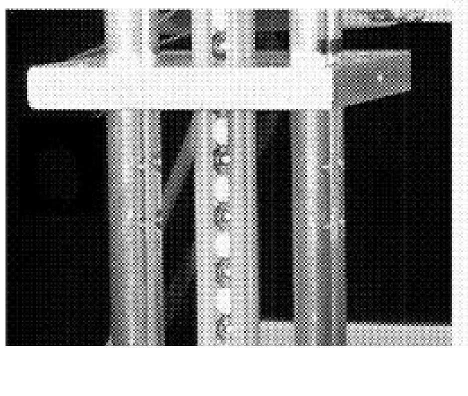


FIG. 7B

[0019] **FIG. 7B** shows a system in which each layer is a molded layer having individual particles of various geometric shapes.

[0020] **FIG. 8** shows a photograph of an experimental assembly used for a study of a dimer chain consisting of alternating stainless steel and Teflon particles.



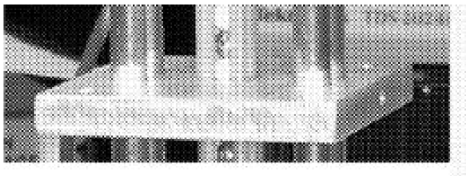


FIG. 8

DETAILED DESCRIPTION

[0021] Granular materials based on geometrical arrangements of spherical beads are the simplest and most common systems used theoretically, numerically, and experimentally for studying the formation and propagation of the highly nonlinear waves in solids. Despite being the most studied example for these systems, they are not the only one possible solution for the creation of systems with a highly nonlinear response. The continuum theory derived for highly nonlinear waves indeed is not limited to the Hertzian interactions (n=3/2) between the discrete components: the theoretical formulation that describes them has been extended and generalized to all nonlinear exponents n, with n.noteq.1. Indeed, a similar power-law type response can be found in many other nonlinear systems. The analytical formulation of the highly nonlinear waves has also been extended to heterogeneous systems composed of "layered" structures. Additional work may be done analytically in parallel with experimental and numerical analysis for periodic heterogeneous nonlinear systems. The presence of periodic "defects" (heterogeneities) is particularly relevant for the design and study of shock protecting structures and energy dissipaters, as the defects play a relevant role in the scattering, redirecting sideways, or localization of energy and in the tunability of the compressive pulses traveling through the material. Such properties, in particular the ones found in heterogeneous granular systems, may provide valid alternatives to the present state of the art shock energy protectors/dissipaters

[0022] The fundamental nonlinear dynamic response present in uniform systems is governed by the wave equation derived and solved in the continuum limit. For highly nonlinear uniform systems, the long wave approximation, derived from the Hertzian interaction law (n=3/2), is shown below in Eq. (2):

u tt = - c 2 { (- u x) 3 / 2 + a 2 10 [(- u x) 1 / 4 ((- u x) 5 / 4) xx] } x Eq . (2) ##EQU00001##

where u is the displacement, a is the particle's diameter, c is a material's constant, and the subscripts indicate the derivative. The constant c in Eq. (2) is given by Eq. (3) as shown below:

c 2 = 2 E .pi..rho. 0 (1 - v 2) Eq . (3) ##EQU00002##

where E is the Young's modulus, .rho..sub.0 is the density, and v is the Poisson coefficient. The generality of this highly nonlinear wave equation is given by the fact that it includes also the linear and weakly nonlinear wave equations.

[0023] Despite its apparent complexity the closed form solution of Eq. (2) can be obtained. For the case of a granular system with no or very weak precompression acting on it, the exact solution exists in the form as shown below in Eq. (4):

.xi. = (5 V p 2 4 c 2) 2 cos 4 (10 5 a x) Eq . (4) ##EQU00003##

where .zeta. represents the strain and V.sub.p the system's velocity. The solitary shape, if the initial prestrain .zeta..sub.0 is approaching 0, can be taken as one hump of the periodic solution (provided from Eq. (4)) with finite wave length equal to only five particle diameters.

[0024] The periodic solution described above demonstrates that in a highly nonlinear medium (such as in "granular crystals") only two harmonics contribute to a stationary mode of propagation of the periodic signal. In analogy with the KdV solutons (as described by Korteveg and de Vries in "On the change of form of long waves advancing in a rectangular canal, and on a new type of long stationary Waves," London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, ser. 5, 39, pp. 422-443. (1895)), the highly nonlinear solitary waves are supersonic, which means that their phase velocity is larger than the initial sound velocity (c.sub.0) in the nonlinear medium (especially in the case of an uncompressed system, in which the c.sub.0=0). One of their unique feature is the independence of their width on the amplitude (their spatial size is always .about.5 particles diameter, no matter what wave amplitude or wave speed is present in the system) which makes them one of the most tractable forms of "compactons" (described by Rosenau and Hyman in "Compactons: Solitons with finite wavelength," Physical Review Letters 70, 564 (1993)). This property is quite different from the properties of weakly nonlinear KdV solitary waves and it is very important for the use of these solitary waves as information carriers and in signal transformation devices.

[0025] The speed of the solitary wave V.sub.s, as a nonlinear function of the maximum particle dynamic strain in purely highly nonlinear systems, can be expressed as shown below in Eq. (5):

V s = 2 5 c .xi. m 1 / 4 = 0.6802 (2 E a .rho. 3 / 2 (1 - v 2)) 1 / 3 F m 1 / 6 Eq . (5) ##EQU00004##

where F.sub.m is the maximum dynamic contacts force between the particles in the discrete chain. This relationship uncovers a useful characteristic of such waves, predicted by the theory and validated numerically and experimentally: their tunability. By changing the mechanical and/or the geometrical properties of the high nonlinear medium supporting the formation of highly nonlinear solitary waves, the shape and the properties of the traveling pulse can be tuned. As such, the solitary waves in the highly nonlinear media can be engineered for specific applications

[0026] The analytical expression for the tunability of the solitary waves speed derived from the discretization of the particles in a precompressed chain may be expressed as shown in Eq. (6) below:

V s = 0.9314 (4 E 2 F 0 a 2 .rho. 3 (1 - v 2) 2) 1 / 6 1 (f r 2 / 3 - 1) { 4 15 [3 + 2 f r 5 / 3 - 5 f r 2 / 3] } 1 / 2 . Eq . (6) ##EQU00005##

[0027] where F.sub.0 represents the static precompression added to the system, f.sub.r=F.sub.m/F.sub.0 and F.sub.m is the maximum contacts force between the particles in the discrete chain. The dependence of the solitary wave properties on the materials parameters is shown in Eq. (5) for a non-prestressed system and in Eq. (6) for a prestressed system. Another feature of the highly nonlinear solitary waves is determined by the fact that the system is size independent and the solitary waves can therefore be scalable to any dimension, according to the needs of each specific application. According to Eqs. (5) and (6), the tunability of the highly nonlinear solitary waves can be achieved varying one or more of the characteristic parameters of the nonlinear media.

[0028] The generalized form of the partial differential equation describing the highly nonlinear regime in binary heterogeneous periodic systems has been and can be expressed as shown in Eq. (7) below:

U.sub..tau..tau.=u.sub.x.sup.n-1u.sub.xx+Gu.sub.x.sup.n-3u.sub.xx.sup.3+Hu- .sub.x.sup.n-2u.sub.xxu.sub.xxx+Iu.sub.x.sup.n-1u.sub.xxxx Eq. (7)

where u is the displacement, .tau. is a rescaled time, n is the nonlinear exponent found in Eq. (1) and the explicit expression of the parameters I, H, G can be found in Porter, M.A.; Daraio, C.; Herbold, E. B.; Szelengowicz, I.; Kevrekidis, P. G. "Highly nonlinear solitary waves in phononic crystal dimers" Physical Review E, 77, 015601 (R), 2008.

[0029] The solution for Eq. (7), describing the shape and properties of the highly nonlinear solitary waves, from direct integration is of the form shown in Eq. (8) below:

u = v = B cos 2 n - 1 (.beta. .xi.) , Eq . (8) ##EQU00006##

where B = (.mu. [.beta. 2 s (s - 1)]) 1 / n - 1 , .beta. = .sigma. (1 - .eta.) 2 and s = pI . ##EQU00007##

[0030] Highly nonlinear granular systems composed of spherical beads have been extensively studied in the past. Embodiments of the present invention comprise systems that may deviate from the classical Hertzian approach associated with systems using chains of spherical beads. Systems that do not rely upon chains of spherical beads include: chains composed of O-rings described by Herbold and Nesterenko in "Solitary and shock waves in discrete strongly nonlinear double power-law materials," Applied Physics Letters, 90, 261902, (2007), and complex 2-D and 3-D granular assemblies as described by Goddard in "Nonlinear Elasticity and Pressure-Dependent Wave Speeds in Granular Media," Proc. R. Soc. Lond. A 430, 105 (1990). Coste and Falcon describe the possibility of obtaining deviations from the Hertzian type response also in 1-D chains of spherical beads composed of "soft" materials (i.e. bronze or polymer) in "On the validity of Hertz contact law for granular material acoustics," European Physical Journal B, 7, 155. (1999).

[0031] An embodiment of the present invention is a system that uses aligned stainless steel elliptical grains, such as those shown in FIG. 1. FIG. 1 shows a photograph of elliptical particles fabricated from stainless steel. Results demonstrate that 1-D chains composed of elliptical particles support the formation and propagation of highly nonlinear solitary waves when subjected to impulsive loading, following a non-Hertzian contact interaction law. FIG. 2A shows an experimental set up of a vertically stacked chain 100 of 20 stainless steel elliptical beads 130. Piezoelectric sensors are embedded in two sensor particles 150 at particles 7 and 12, as well as at a wall sensor 170 in contact with a wall 110. FIG. 2B shows the sensor particle 150 having a piezo-sensor 154 encapsulated in a glue layer 153 and sandwiched between two particle caps 151. Particle sensor leads 152 provide an electrical output from the sensor particle 150. Similarly, the wall sensor 170 shown in FIG. 2C has a piezo-sensor 174 encapsulated in a glue layer 173 sand sandwiched between two wall sensor caps 171. Wall sensor leads 172 provide an electrical output from the wall sensor 170.

[0032] FIG. 3 shows the formation of solitary waves excited by impact in the chain of twenty stainless steel elliptical beads. The twenty stainless steel elliptical beads (supplied by Kramer Industries) had m=0.925 g.+-.0.001 g; minor axis equal to 4.76 mm; major axis equal to 10.16 mm; modulus of elasticity equal to 193 GPa; and v equal to 0.3. The beads were stacked in a vertical aluminum guide. Piezoelectric sensors were provided as shown in FIGS. 2A-2C by gluing custom micro-miniature wiring (supplied by Piezo Systems, Inc.) between the two caps of an elliptical bead cut length-wise. The sensors were calibrated to produce force versus time data by assuming conservation of linear momentum following the impact of a free falling bead. Impact was generated with 3.787 g striker traveling at 0.75 m/s striking the top particle in the chain; the average wave speed was calculated at 525 m/s. In FIG. 3, line 191 represents the data measured at the top sensor particle 150, Line 193 represents the data measured at the lower sensor particle 150, and line 195 represents the data measured at the wall sensor 170. It is noted that although highly nonlinear wave theory was derived for uniform systems with a general exponent governing their contact interaction law, experimental validation is typically provided only through Hertzian interactions and/or using spherical particles.

[0033] According to some embodiments of the present invention, the empirical determination of the "n" exponent in Eq. (1) for elliptical grains may be determined by either of the following two methods: a first method based on the single particle impact and conservation of momentum; or a second method based on the Force (F.sub.m)-velocity (V.sub.s) scaling similar to that described, for example, in "On the validity of Hertz contact law for granular material acoustics," European Physical Journal B, 7, 155. (1999) or in Porter et al., "Highly nonlinear solitary waves in phononic crystal dimers" Physical Review E, 77, 015601 (R), 2008, for dimer chains. The second method, tested on spherical beads to verify its robustness has been shown to be reliable. The power law fit provided a value of the contact interaction exponent for irregular elliptical beads n.about.1.449, proving a deviation from classical Hertzian response.

[0034] A determination of the "n" exponent from Eq. (1) for elliptical particles was made by analyzing the data summarized in FIG. 3 using the second method described above. The average velocity of the solitary wave was determined by dividing the distance between the centers of the two particle sensors (equal to 5 particle diameters) by the time interval between the maximum force seen at these sensors. The average maximum force of the highly nonlinear pulses was determined by averaging the force amplitudes at the two sensor particles. The average velocity and average force amplitude for the solitons generated through various impulsive forces provided for force versus velocity data. Evaluation of the power-law relationship in light of the equations above provides that, for the measured elliptical particles, n.about.1.449.

[0035] An estimate of the "n" exponent from Eq. (1) for elliptical particles using the first method described above was also made by impacting a fixed sensor with an elliptical particle. To ensure that the particle retained proper orientation throughout free fall and contact with the sensor, a plastic guide rod was cemented to the upper portion of the particle. Assuming conservation of linear momentum and integrating numerically the Force versus time plots using Euler's method (beginning at the point of first contact between the elliptical particle and the sensor (t.sub.0) until the particle reached a full stop in its descent (v(t)=0)), velocity versus time was obtained. Using the same procedure, the resulting velocity versus time curve was integrated again to produce displacement versus time. By matching experimentally obtained force data with calculated displacement data, a force versus displacement curve was produced. Best fit analysis of each resulting force versus displacement curve enabled determination of the exponent "n".

[0036] Embodiments of the present invention are not limited to systems and methods using elliptical beads. The results described earlier for 1-D chains of elliptical beads show the formation and propagation of highly nonlinear pulses in non-Hertzian systems and support the examination and use of 1-D granular chains composed of particles with different geometries. The selection of these grains having more complex non-spherical shapes may generally require the empirical determination of the contact interaction laws governing the Force (F.sub.m)-displacement (.delta.) response between the fundamental components of the systems; in particular for the cases where the analytical derivation of the contact mechanics has not been provided.

[0037] Other embodiments according to the present invention include systems and methods using particles having cylindrical geometry. One-dimensional arrays of cylinders (as opposed to the elliptical particles described earlier) may offer a potential for the practical assembly of 3-D systems and enable a large range of tunability of the level of nonlinearity (value of the exponent "n" in Eq. (1)). Such tunability can be achieved by the simple variation of the reciprocal axial orientation between the cylinders in the chain as described in additional detail below.

[0038] FIGS. 4A and 4B illustrate relative orientations of a pair of cylindrical particles. In FIG. 4A, the axis of the particles are oriented parallel to each other with .theta.=0.degree.. In FIG. 4B, the axis of the particles are oriented perpendicular to each other with .theta.=90.degree.. FIG. 4C shows a schematic diagram of a 3-D system assembled from an array of cylindrical contacts having vertical orientations of 0.degree.<.theta.<90.degree.. FIG. 4D illustrates the vertical alignment of the cylindrical contacts in FIG. 4C.

[0039] A 1-D array of cylinders with axis oriented parallel with respect to each other (as in FIG. 4A) do not support the formation of clean solitary waves because of their linear contact interaction dynamics. This represents a limit case in Hertz's approach to the study of interaction laws between solids of revolution and presents no simple analytical form for its description. An axial misalignment of 0.degree.<.theta.<90.degree. where .theta. represents the angle between the axis of two consecutive cylinders in the chain (such as that shown in FIGS. 4C and 4D), brings back the system to a "manageable" geometry, falling back within the Hertzian treatment (n=1.5). The other limiting case (.theta.=90.degree., such as in FIG. 4B) falls back into a second limit example and does not have a simple analytical solution for the contact law.

[0040] Experimental results from a 1-D stack of cylinders oriented at 0.degree. and 90.degree. with respect to each other has shown that by simply changing the angle of orientation between the axis of the cylinders it is possible to change dramatically the wave propagation response of the system. Cylinders oriented at 0.degree. (parallel axis) excited by an impulse do not show the formation of highly nonlinear solitary waves (but rather presented the propagation of shock-like pulses). Chains with cylinders oriented in a 90.degree. degrees configurations support formation and propagation of highly nonlinear solitary pulses analogous to the one observed in chains of spherical beads. FIG. 5 shows experimental data obtained from a vertically aligned chain of cylinders oriented perpendicular to each other. The chain consisted of a total of 38 cylinders. Piezogauges were inserted at a wall and in 3 of the cylinders within the chain. The data obtained from the wall sensor is shown at line 196; the data from the cylinders within the chain are shown at lines 197, 198, and 199.

[0041] Rod-based structures similar to the one depicted in FIG. 4C can be tuned by applying variable static precompression. The application of such static force can be achieved, for example, by using tension cords, strings or nets wrapped on two opposing sides of the outer cylinders or rods edges. The control over the amount of compression applied by such elements to the assembled rods can be obtained by using small dynamometers or by tightening screws with measured torques. FIG. 6 shows a schematic diagram of a rod-based 3-D system 200 using precompression. The system has arrays of lateral rods 201 alternating with arrays of perpendicular rods 203. The outside ends of the lateral rods 201 are compressed together with tension cords 210 or other such fastening apparatus. Similarly, the outside ends of the perpendicular rods 203 are compressed together with tension cords 210 or other such fastening apparatus. A dynamometer 211 within each tension cord 210 may be used to measure and adjust the amount of precompression.

[0042] To obtain the dynamic response "purely" from the granular system without the influence of the matrix between the chains, it is possible to create desired three-dimensional systems in a cubic or hexagonal pattern at different length scales assembling the particles (elliptical, conical, rods, etc) in a layer-by-layer process. The new composite granular structures can be manufactured in large quantity in industrially viable processes. Depending upon the fabrication process used, it may be possible to create light weight, tunable and even flexible or wearable protective layers, all exploiting the new properties offered by the highly nonlinear wave theory discussed above. Such protective systems may allow for sideway impulse redirection, energy trapping and/or energy dissipation. FIG. 7A shows a system 230 in which one dimensional chains 231 of particles 232 (that may have various geometrical shapes) are held to each other at weld points 233 are assembled into layers for a 3-D array of particles. Note that in FIG. 7A, the particles 232 may be welded, glued or electrostatically/magnetically interacting together in the horizontal direction, but are merely contacting one another in the vertical direction. FIG. 7B shows a system 240 in which each layer 241 is a molded layer having individual particles 242 of various geometric shapes. Note that in FIG. 7B (similar to 7A), the layers 241 comprise molded particles in the horizontal direction, but are the layers are 241 are merely contacting one another in the vertical direction. As discussed above, the systems shown in FIGS. 7A and 7B may also have precompression applied.

[0043] The methods and systems described above have application for acoustic band gaps in tunable highly nonlinear crystals. Linear or weakly nonlinear periodic crystals with two or more atoms per primitive basis (precompressed dimer or trimer chains as described in Porter et al., "Highly nonlinear solitary waves in phononic crystal dimers," Physical Review E, 77, 015601 (R), 2008. and Porter et al., "Propagation of Highly Nonlinear Solitary Waves in Phononic Crystal Dimers and Trimers," Physica D, submitted 2007) are known to have a classical phonon dispersion relation in which for each polarization mode in a given propagation direction, the dispersion relation develops two branches, known as the acoustical and optical branches. Depending on such relation, the system can present one or more frequency band gaps between the branches as a function of the mass ratio in the system and the precompression level applied to it. For a simple cubic crystal where atoms (analogous to Hertzian grains in the systems described above) of mass ml lie on one set of planes and atoms of mass m.sub.2 lie on planes interleaved between them, the lower bound (f.sub.1) and upper bound (f.sub.2) of the bandgap can be expressed by Eq. 9 shown below:

f 1 = 1 2 .pi. (2 .beta. m 1) 1 / 2 , f 2 = 1 2 .pi. (2 .beta. m 2) 1 / 2 . Eq . (9) ##EQU00008##

In Eq. 9, .beta. is a constant proportional to the material's parameters (Youngs modulus, Poisson's coefficient and particle's radii) and static precompression applied to the system (see. For example, Herbold, E. B.; Kim, J.; Nesterenko, V. F.; Wang, S.; Daraio, C. "Tunable frequency band-gap and pulse propagation in a strongly nonlinear diatomic chain" Acta Mechanica (submitted and published online), 2008).

[0044] Preliminary results were obtained from the study of dimer systems of stainless steel and Teflon particles excited by continuous sinusoidal signals at variable frequencies. FIG. 8 shows a photograph of the experimental assembly used for the study in which the dimer chain consisted of alternating stainless steel and Teflon particles. The band gap calculated for this model system was between .about.7-14 kHz. The excitations with frequencies comprised in the estimated gap (as provided in Eq. (9)) remained confined in the exciter particle and its immediate surrounding.

[0045] A numerical model for a 1-D generic granular system according to embodiments of the present invention treats particles as rigid bodies connected by nonlinear springs to study acoustic excitations in the systems and the presence of band gaps, wave decay and possible presence of gap solitons deriving from the nonlinearity of the system response. Such a model can show that when a pulse was excited within the gap, the system responds with a rapid decay of the initial excitation already within the first 10 particles in the chain, with relevant attenuation of the pulse's intensity in the audible frequency range. Thanks to the high tunability of the highly nonlinear crystals, the forbidden frequency range can be effectively designed and varied at will, simply choosing the appropriate particles' mass ratio and static precompression applied to the system.

[0046] As indicated above, embodiments of the present invention may have particular application to linearized granular crystals (as phononic crystals). Just as crystalline materials can be said to possess a lattice structure, with atoms occupying various positions in the lattice, phononic-crystal engineered composite systems (i.e., "metamaterials") can be pictured as a lattice structure with nano to macro scale particles replacing their atomic counterparts. Such phononic crystals based on granular materials are most fundamentally typified in a statically precompressed one dimensional (1-D) chain of macroscopic particles. Due to zero tensile strength in the particle chain and a power-law relationship between force and displacement, linear, weakly nonlinear or highly nonlinear wave dynamics may arise, enabling the formation and propagation of solitary waves following impulsive loading and yielding desirable properties in their acoustic and mechanical response. Static compression of the particle chain prior to impulsive loading or "pre-compression" as discussed above enables the system to be tuned from highly nonlinear to weakly nonlinear to linear wave dynamics, enabling potential engineering applications in shock absorption, vibration dampening, and acoustic filtering (by forming acoustic band gaps).

[0047] Due to the nonlinear force versus displacement relationship and the discrete nature of granular-crystal systems, solitary (compression) waves readily form. Employing the long wave approximation, L>>a (where L is the width of the solitons and a is distance between particle centers), for any power law material of the form F.varies..delta..sup.n, the speed of a solitary wave is given by Eq. (10) below:

V s = (A n .times. a n + 1) 1 2 .times. 2 n + 1 .times. (.xi. m) (n - 1) 2 Eq . (10) ##EQU00009##

where A.sub.n is some constant dependant upon material properties, a is the particle diameter (distance between two particles centers), n is the exponent governing the force versus displacement relationship, and .zeta..sub.m is the maximum strain in the system.

[0048] Relating .zeta..sub.m to the maximum force in the system (F.sub.m), Eq. (10) can be rewritten as Eq. (11) below:

V s = a .times. 2 .times. A n 1 n (n + 1) .times. m (n - 1 n) .times. (F m) (n - 1) 2 n Eq . (11) ##EQU00010##

Just as pre-compression of a particle chain "tunes" the mechanical response to impulsive loading. Eq. (11) demonstrates that adjusting the exponent (n) provides an additional means of control over linearized granular crystals.

[0049] From an analytical perspective, the discrete nature of a 1-D granular crystal can be ignored if the system is treated as a continuum and if the particles are homogeneous in mass and material characteristics. However, the introduction of new material compositions and/or masses yields a "defect" into the system (i.e., an interface) and causes a breakdown of the analytical description of the system. Such "defects" introduce fundamentally different behavior into the granular medium and may have potential in energy trapping/redirecting, localization phenomena and shockwave mitigation applications. Returning to the test apparatus shown in FIG. 8, the chain of alternating stainless steel and Teflon beads demonstrated the nearly complete energy transfer across the interface between the Teflon and stainless steel beads in the uncompressed case, as shown by the lack of a reflected compression wave into the stainless steel beads. Introduction of multiple "defects" into a 1-D granular crystal through an alternating pattern of different particles/materials like in the case of Teflon and stainless steel beads demonstrates the ability of such a system to transform a shock-like impulse into a sequence of smaller amplitude pulses.

[0050] Observation of solitary waves in a 1-D chain of elliptical beads and empirical measurement of the exponent governing the force versus displacement relationship for elliptical particles provides experimental validation that a non-Hertzian system can support solitary wave propagation. Such an experimental validation also demonstrates that particle geometry changes offer a realizable mechanism for tuning the mechanical and acoustic response of linearized granular crystals.

[0051] The foregoing Detailed Description of exemplary and preferred embodiments is presented for purposes of illustration and disclosure in accordance with the requirements of the law. It is not intended to be exhaustive nor to limit the invention to the precise form or forms described, but only to enable others skilled in the art to understand how the invention may be suited for a particular use or implementation. The possibility of modifications and variations will be apparent to practitioners skilled in the art. No limitation is intended by the description of exemplary embodiments which may have included tolerances, feature dimensions, specific operating conditions, engineering specifications, or the like, and which may vary between implementations or with changes to the state of the art, and no limitation should be implied therefrom. This disclosure has been made with respect to the current state of the art, but also contemplates advancements and that adaptations in the future may take into consideration of those advancements, namely in accordance with the then current state of the art. It is intended that the scope of the invention be defined by the Claims as written and equivalents as applicable. Reference to a claim element in the singular is not intended to mean "one and only one" unless explicitly so stated. Moreover, no element, component, nor method or process step in this disclosure is intended to be dedicated to the public regardless of whether the element, component, or step is explicitly recited in the Claims. No claim element herein is to be construed under the provisions of 35 U.S.C. Sec. 112, sixth paragraph, unless the element is expressly recited using the phrase "means for . . . " and no method or process step herein is to be construed under those provisions unless the step, or steps, are expressly recited using the phrase "comprising step(s) for . . . "

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USPA20090204344

METHOD AND APPARATUS FOR NONDESTRUCTIVE EVALUATION AND MONITORING OF MATERIALS AND STRUCTURES

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EC: G01N29/34B; G01N29/24E IPC: G01N29/12; G01N29/04; G01N29/12; (+1)

Abstract -- A method and apparatus for nondestructive evaluation (NDE) of structures and materials using a highly nonlinear medium for the generation and detection of one or multiple highly nonlinear pulses (or highly nonlinear waves) impinging on a material or structure. The apparatus includes pulse exciters that induce the propagation of highly nonlinear, weakly nonlinear or linear stress waves in the material, system, or structure to be inspected and/or detectors for the observation and the detection of the output waves from the material/structure being tested. The NDE method includes the use of the tunable highly nonlinear apparatus as impulse exciter alone, or in combination with an accelerometer or a nonlinear sensor to detect the outgoing pulse.

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Intern'l Class: G01N 29/11 20060101 G01N029/11; G06F 19/00 20060101 G06F019/00

Description

BACKGROUND

[0002]1. Field

[0003] This disclosure relates to a method and apparatus for the excitation and transmission of highly nonlinear pulses with selectable pulse properties into a structure or material and the detection of such pulses from the structure or material. More particularly, the present disclosure describes a method and apparatus for exciting a selectable number of controllable highly nonlinear pulses with desired shapes, amplitudes, frequencies and/or durations, which may then be used for nondestructive evaluations and/or structural health monitoring.

[0004] 2. Description of Related Art

[0005] Non-destructive evaluation of a material or structure may be accomplished through the use of impact testing. In impact testing, the material or structure is typically struck with an impact device and sound waves propagating through the material or structure are then measured to provide some indication of defects within the material or structure. See, for example, U.S. Pat. No. 5,165,270 to Sansalone, et al., dated Nov. 24, 1992. In U.S. Pat. No. 5,165,270, the impact device is a number of differently weighted spheres that are each designed to produce a different duration of impact, thereby imparting different stress waves into the structure to be tested. The different stress waves have different frequency values depending on the impact duration. Each sphere is disposed on one end of a spring-steel rod. At the start of the test, a selected sphere is in a resting position. The sphere is withdrawn from the rest position by a pair of jaws to a given height above the structure. This action deflects the spring-steel rod, thus increasing the potential energy of the impact sphere. At a predetermined release point, the sphere is released causing it to impact the structure and impart a given energy to the structure. The impact produces stress (sound) waves that are reflected from the external surfaces and/or internal defects of the structure. The reflected waves are detected by a transducer that converts the normal surface displacements caused by the waves into an electrical signal. The electrical signal is then processed to provide an amplitude/frequency spectrum indicative of either the thickness of the structure or the defects disposed therein.

[0006] Other impact testing apparatus and techniques are known in the art, but generally use approaches similar to that described above, i.e., strike the material to be tested and measure the stress wave propagation. The impact devices (i.e., strikers) used in impact-testing technology typically cost several hundreds of dollars or more and need coupling to a signal conditioner. Line-powered signal conditioners are used to power sensors and condition their output signals for transmittal to readout and recording instruments. Impact hammers are used for delivering impulse forces into test specimens and the signal conditioner is used to provide electrical measurement signals of the amplitude and frequency content of the applied force. Hammers and conditioners used for non-destructive evaluation may be very expensive. Embodiments of the present invention as described below may provide for less costly apparatus for nondestructive evaluation of materials and structures.

SUMMARY

[0007] Embodiments of the present invention rely on the use of highly nonlinear waves (HNWs), including highly nonlinear solitary waves (HNSWs), which can form and travel in highly nonlinear systems (i.e., systems that may comprise granular, layered, fibrous or porous materials). Compared to conventional stress waves used in prior art systems using sonic-, ultrasonic-, or impact-based technology, HNWs offer significantly higher tunability in terms of wavelength, wave speed (proportional to the wave amplitude and to the material's properties), number of generated pulses, and amplitude control in a simple and reproducible setup that can be adjusted at will.

[0008] Embodiments of the present invention may provide for improvements over prior art systems that include: 1) larger tunability range of the frequency, amplitude and velocity of induced pulses resulting in a broader range of sizes of detectable cracks, defects, and inclusions in a material (i.e., multiscale defects sensitivity); 2) enhanced repeatability of measurements, improving a measurements system's reliability and avoiding the required high operator skills typically needed by prior art methods; 3) simpler and more scalable design of the instruments within the measurement system (such as wave actuators and sensors) to different dimensions (which may also provide more versatility of applications); 4) reduced power requirement characteristics of the instruments; and 5) reduced cost of assembling and manufacturing of the process components, sensors and actuators (up to 2 orders of magnitude lower than present commercially available impact hammers).

[0009] Some embodiments of the present invention comprise methods and apparatus for nondestructive evaluation and/or structural health monitoring (NDE/SHM) based on highly nonlinear sensors and/or actuators combined together (fully nonlinear system) or coupled with conventional sensing/actuating methods. For example, one embodiment comprises a NDE/SHM method in which a highly nonlinear actuator is used in combination with a classical receiver (such as an accelerometer, laser interferometer, piezogauge or other detectors known in the art), where the actuator provides an input to a material to be inspected and the classical receiver measures the output. Another embodiment comprises an NDE/SHM method in which classical impact echo/tap testing methods of actuation are used together with a highly nonlinear receiver, where the classical impact/tap test provide input and the highly nonlinear receiver measures the output. Still another embodiment comprises an NDE/SHM method in which a highly nonlinear actuator and a highly nonlinear receiver are used together, where the actuator provides the input and the receiver measures the output.

[0010] An embodiment of the present invention is a method for performing an inspection of an element or structure comprising: generating one or more highly nonlinear waves; directing the one or more highly nonlinear waves into the element or structure to be inspected; and, detecting pulses deriving from the waves directed into the element or structure after the waves have propagated through at least a portion of the element or structure to be inspected.

[0011] Another embodiment of the present invention is a system for inspecting an element or structure comprising: a highly nonlinear wave actuator, wherein the actuator is configurable to impinge highly nonlinear pulses to the element or structure to be inspected, and a pulse detector configurable to detect pulses from the actuator propagating through at least a portion of the element or structure to be inspected.

[0012] Still another embodiment of the present invention is A method for performing an inspection of an element or structure comprising: generating an inspection pulse; directing the inspection pulse into the element or structure to be inspected; directing the inspection pulse after it has propagated through at least a portion of the element or structure to be inspected into a nonlinear receiver; and detecting the inspection pulse after it has propagated through at least a portion of the nonlinear receiver.

[0013] Still another embodiment of the present invention is A system for inspecting an element or structure comprising: a pulse actuator, wherein the actuator is configurable to apply pulses to the element or structure to be inspected, and a nonlinear receiver configurable to detect pulses from the actuator propagating through at least a portion of the element or structure to be inspected.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0014] **FIG. 1A** shows a schematic representation of a system for production and/or detection of highly nonlinear waves.

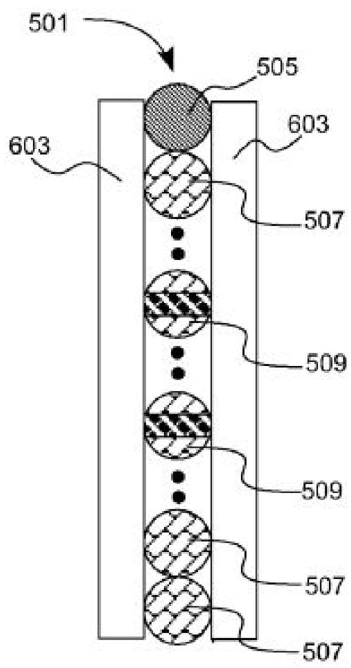


FIG. 1A

[0015] **FIG. 1B** illustrates a bead with an embedded piezoelement.

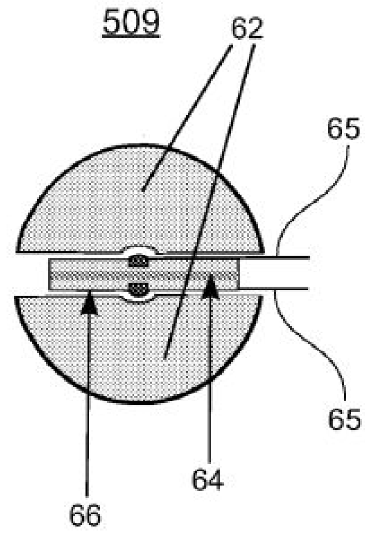


FIG. 1B

[0016] **FIG. 2A** illustrates a system for producing or detecting highly nonlinear waves.

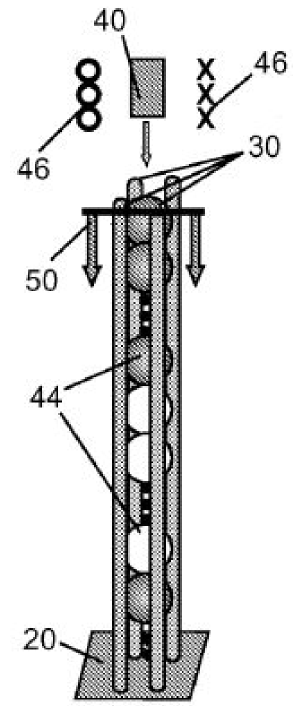


FIG. 2A

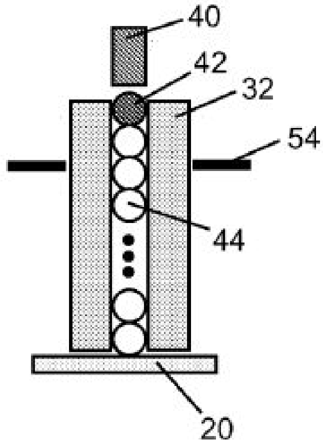
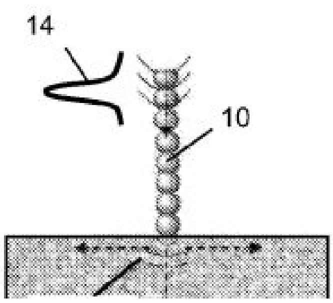


FIG. 2B

[0017] **FIG. 2B** illustrates a system for producing or detecting highly nonlinear waves.

[0018] **FIG. 3A** is a schematic diagram representing the creation, propagation and detection of highly nonlinear solitary waves in relation to a bulk highly nonlinear, weakly nonlinear, or linear medium.



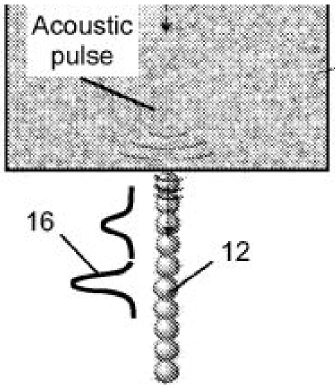


FIG. 3A

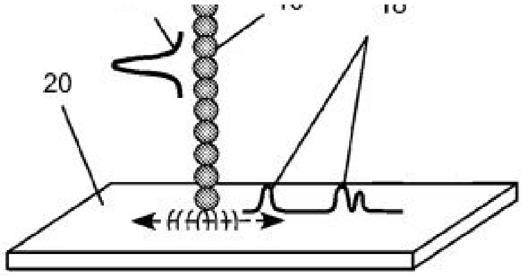


FIG. 3B

[0019] **FIG. 3B** is a schematic diagram representing the transmission of highly nonlinear waves in waveguide structures made of highly nonlinear, weakly nonlinear, or linear medium.

[0020] **FIG. 4** depicts a system where a highly nonlinear actuator is used in combination with a classical receiver.

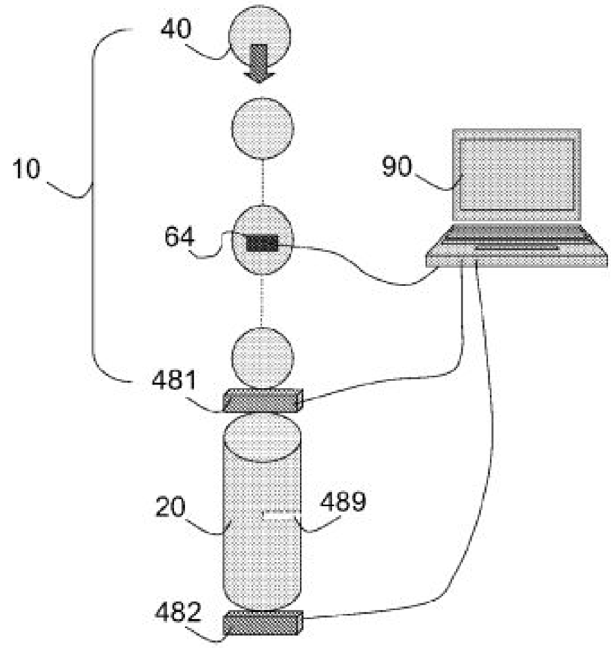
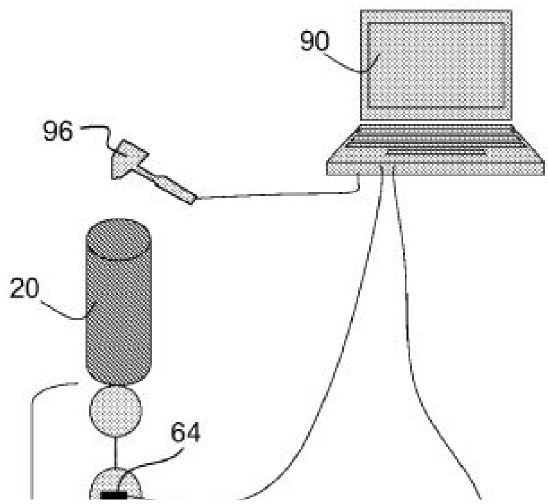


FIG. 4

[0021] **FIG. 5** depicts a system where a classical impact echo/tap testing hammer is used in combination with a highly nonlinear receiver.



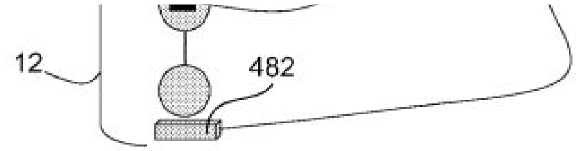


FIG. 5

[0022] **FIG. 6** depicts a system where a highly nonlinear actuator is used in combination with a highly nonlinear receiver.

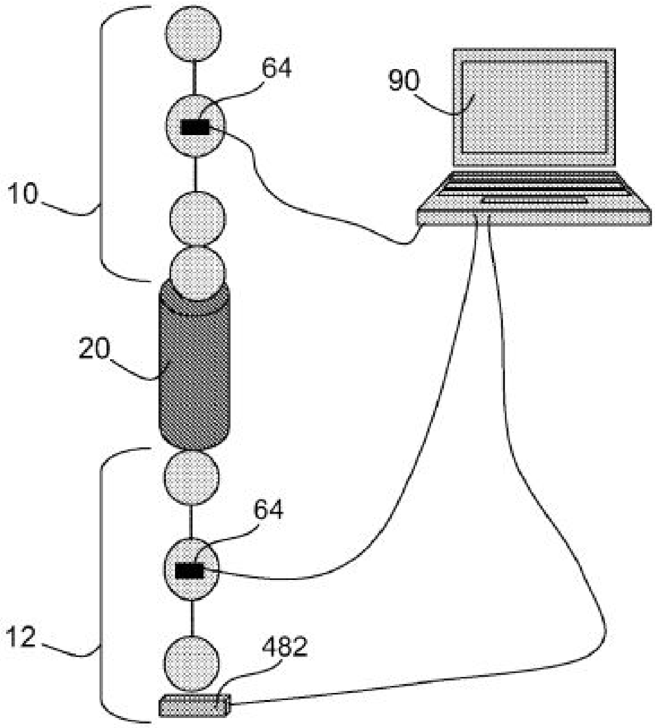


FIG. 6

[0023] **FIG. 7** is a flow chart showing steps of a method for performing nondestructive evaluations and structural health monitoring.

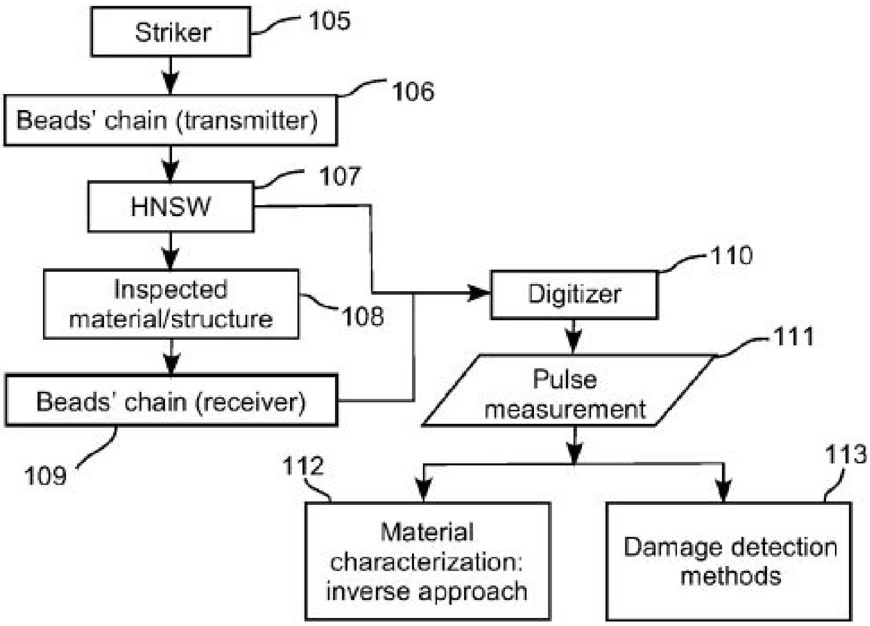


FIG. 7

[0024] **FIG. 8** is a flow chart showing steps for characterizing a material by using an inverse approach.

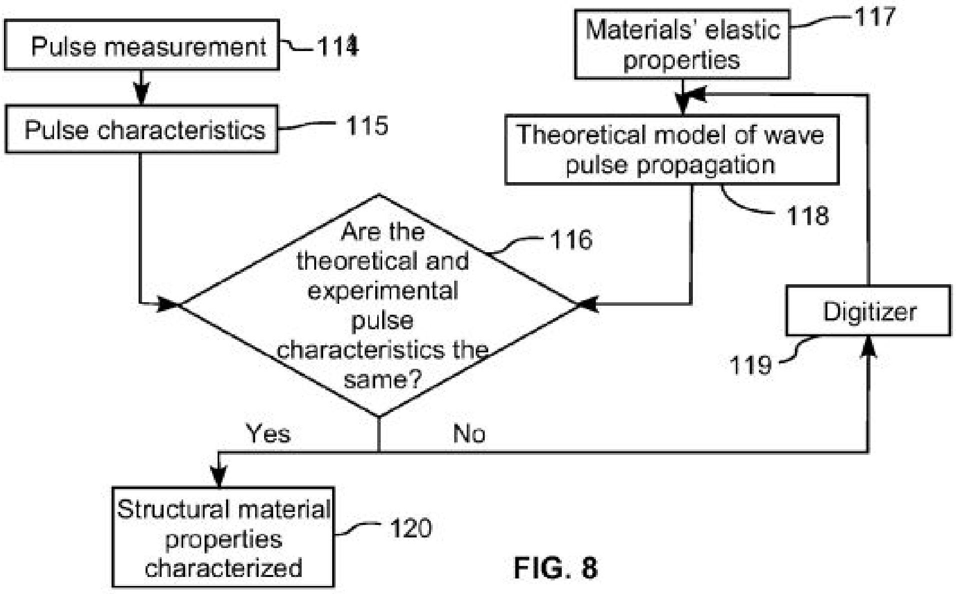


FIG. 8

[0025] **FIG. 9** is a flow chart showing steps for determining whether a material or structure has any damages based on highly nonlinear wave measurements.

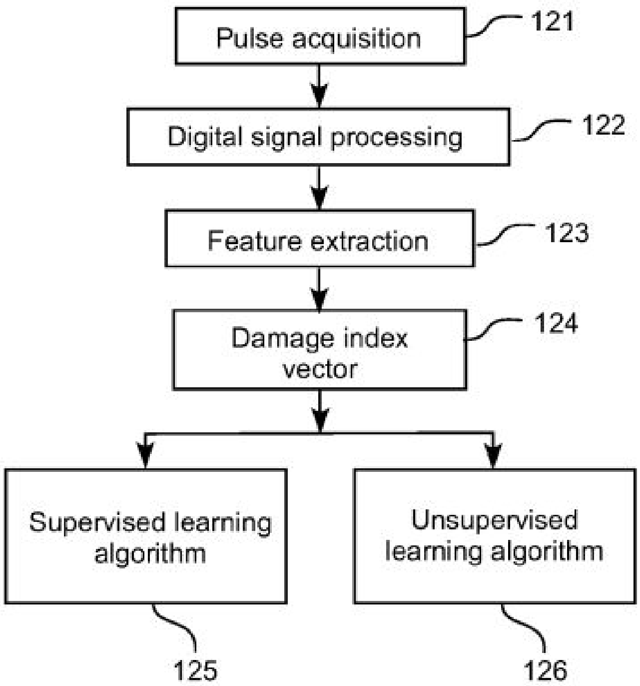
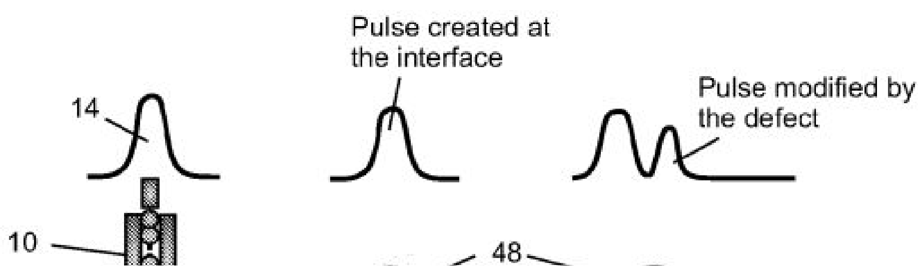


FIG. 9

[0026] **FIG. 10** illustrates the application of a highly nonlinear solitary wave to a damaged structure and propagation of the highly nonlinear solitary wave through the structure and a test setup to detect the damage.



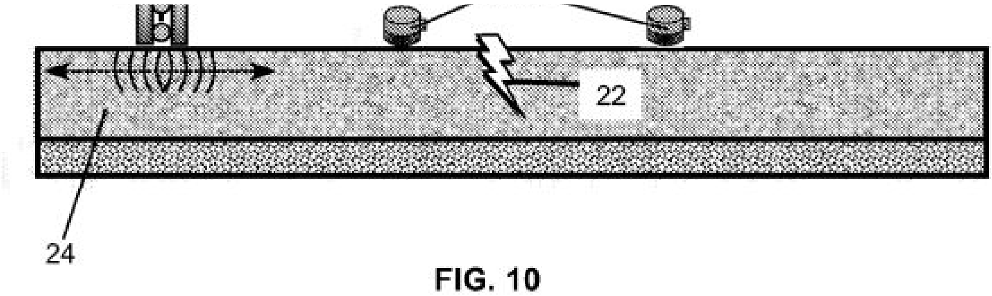


FIG. 10

[0027] **FIG. 11** depicts an undamaged seven wire steel strand and a damaged seven wire steel strand and the application of a highly nonlinear solitary wave thereto.

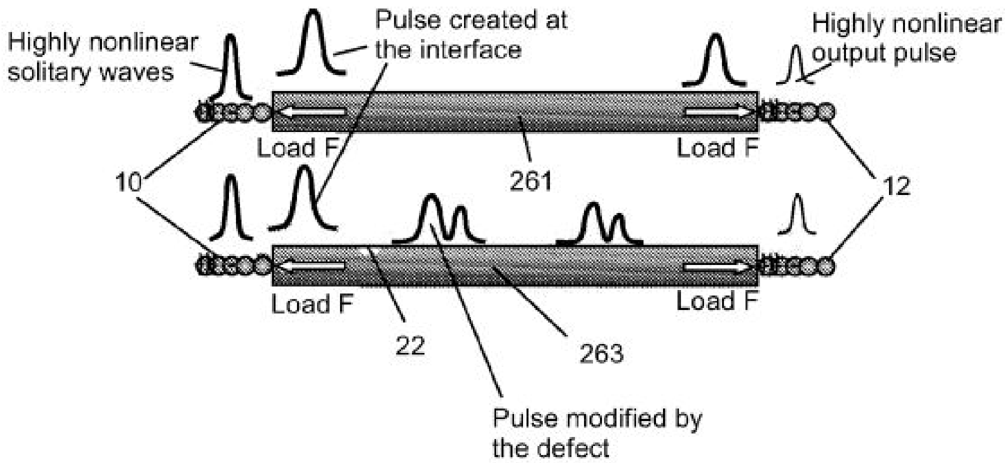


FIG. 11

[0028] **FIGS. 12A and 12B** show experimental results where highly nonlinear solitary wave induced pulses are propagated within a steel rod.

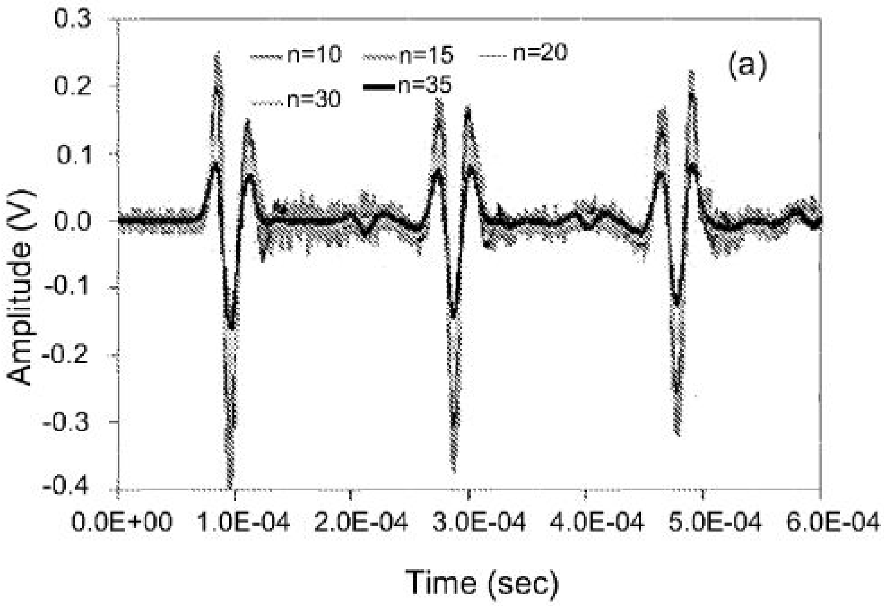
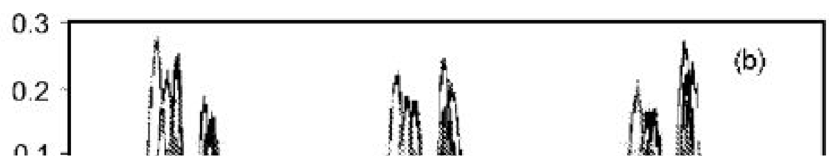


FIG. 12A



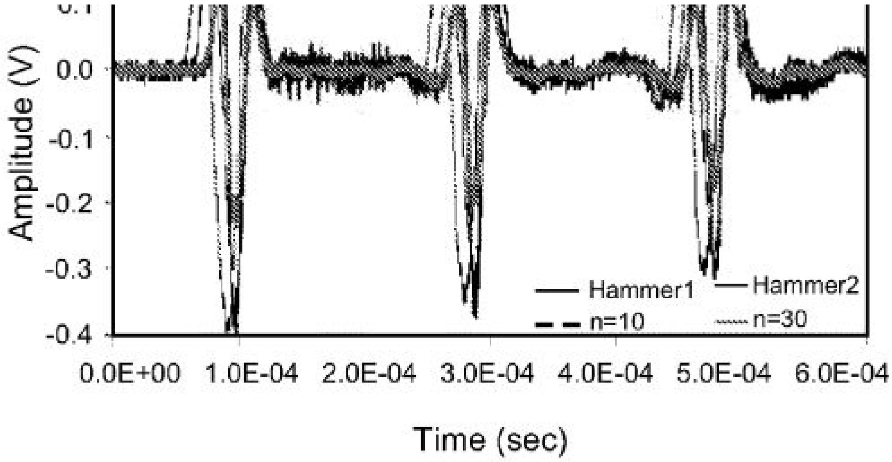


FIG. 12B

[0029] **FIGS. 13A and 13B** show experimental results where highly nonlinear solitary wave induced pulses are propagated within a steel rod using a test setup similar to that depicted in FIG. 4.

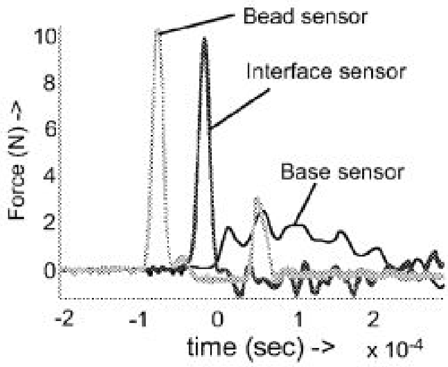


FIG. 13A

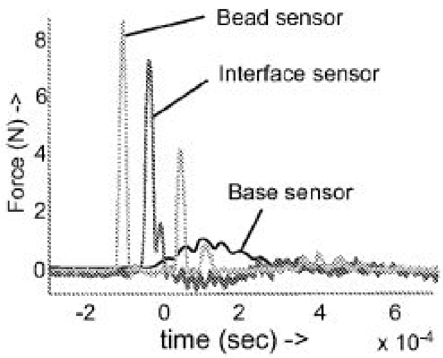


FIG. 13B

[0030] **FIGS. 14A and 14B** show experimental results where highly nonlinear solitary wave induced pulses are propagated within a steel rod using a test setup similar to that depicted in FIG. 4, but with only two sensors.

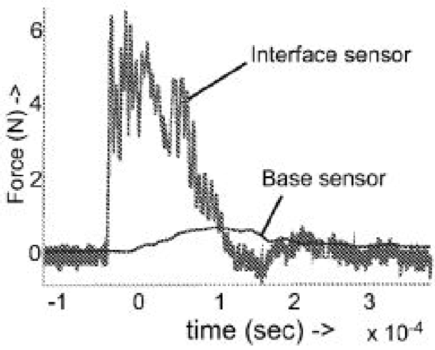


FIG. 14A

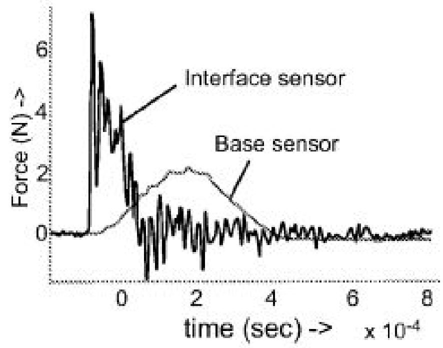
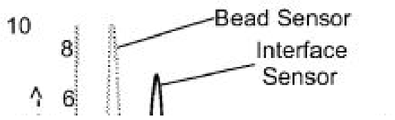


FIG. 14B

[0031] **FIGS. 15A and 15B** show time history results where highly nonlinear solitary wave induced pulses are propagated within a steel rod and precompression is used.



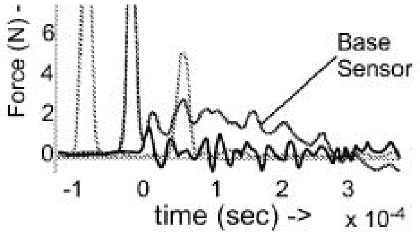


FIG. 15A

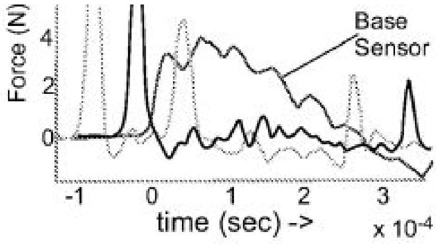


FIG. 15B

[0032] **FIGS. 16A and 16B** show frequency-intensity results where highly nonlinear solitary wave induced pulses are propagated within a steel rod and precompression is used.

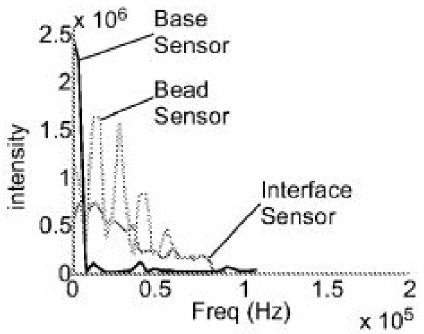


FIG. 16A

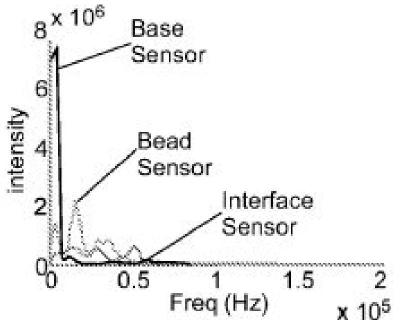


FIG. 16B

[0033] **FIG. 17** shows a system for automated evaluation and monitoring of pavements, railroads, floor spaces and other such structures.

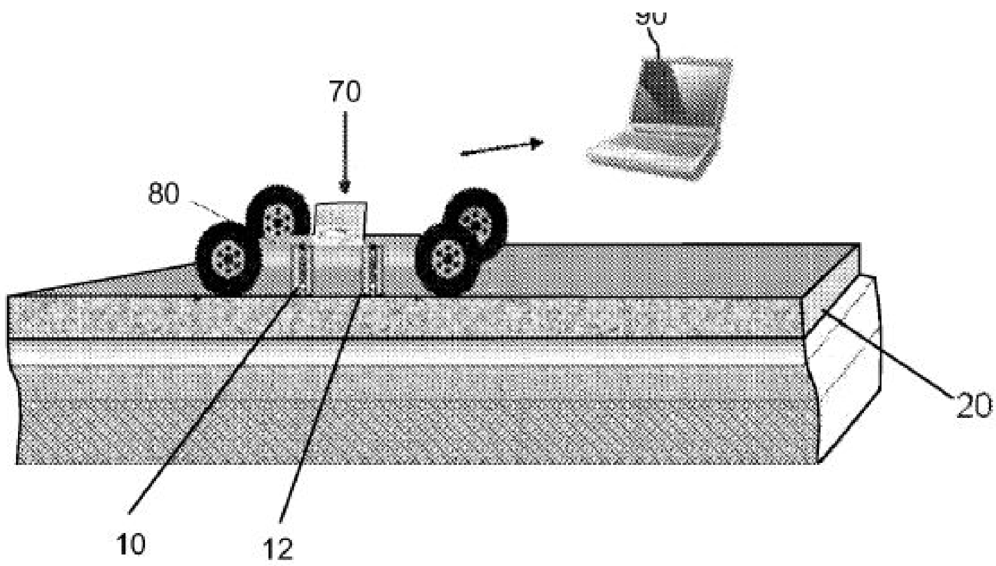


FIG. 17

DETAILED DESCRIPTION

[0034] Embodiments of the present invention provide for nondestructive evaluation and monitoring of materials and structures through the use of highly nonlinear pulses and waves generated in one dimensional chains of granular components. In this disclosure, the granular components or grains may comprise granular matter, which is defined as an aggregate of particles or layers in elastic contact with each other, preferably in linear or network shaped arrangements. While embodiments of the present invention use highly nonlinear pulses and waves, additional advantages may be provided when highly nonlinear solitary waves or pulses are used, generated, and/or detected. For purposes of this disclosure, highly nonlinear solitary waves are to be considered as a specific case of highly nonlinear waves. Additionally, highly nonlinear solitary pulses are to be considered as a specific case of highly nonlinear pulses. Hence, any references to highly nonlinear waves herein are to be considered as including highly nonlinear solitary waves and any references to highly nonlinear pulses herein are to be considered as including highly nonlinear solitary pulses unless otherwise denoted.

[0035] The contact interaction between the grains is regulated by the highly nonlinear force F--displacement .delta. relationship shown in Eq. 1:

F.apprxeq.A.delta..sup.n (Eq. 1)

where A is a material's parameter and n is the nonlinear exponent (with n>1). An unusual feature of the granular state is the negligible linear range of the interaction forces between neighboring particles resulting in zero sound speed in an uncompressed material. This makes the linear and weakly nonlinear continuum approaches based on Korteveg-de Vries (KdV) equation invalid and places granular materials in a special class according to their wave dynamics. The dynamic response of granular materials is controlled by the highly nonlinear wave theory that supports the formation and propagation of highly nonlinear compact solitary waves.

[0036] In granular materials composed by perfectly spherical beads, the highly nonlinear behavior stems from the dynamics of the contact interactions, regulated by Hertz law, for which the exponent n in Eq. 1 is equal to 1.5. This highly nonlinear response can also be found in many other nonlinear systems composed by grains with different geometries and the theoretical formulation has been extended and generalized to all nonlinear exponents n, with n.noteq.1. For example, other geometries may include irregular grains with conical contacts where n=2; forests of vertically aligned carbon nanotubes where n=2.2; transverse vibration in a fiber with discrete particles where n=3 and plug chain gas-liquid systems where n=3. The continuum treatment of the highly nonlinear wave theory extends to periodic heterogeneous media, such as, granular systems where the particles composing the chain are not identical, and periodic defects alternate throughout its length.

[0037] Highly nonlinear solitary waves are stationary pulses forming in ordered granular media by the balancing effects of their geometric nonlinearity and the dispersion present in the medium. A unique feature of the highly nonlinear solitary waves (that makes them different from all other previous solitary waves or solitons described in various other physical systems, such as in fluids, atomistics and electromagnetic waves), is the independence of their wave width from their amplitude. For granular systems, in which Hertz law is valid and the exponent n=1.5, their spatial size is always 5 particles diameter, no matter what wave amplitude or wave speed is present in the system. Using the notation found in the most general treatment of the nonlinear wave theory, the wave equation for a uniform highly nonlinear system, derived from the Hertzian interaction law, is shown in Eq. 2 below:

u.sub..tau..tau.=u.sub.x.sup.n-1u.sub.xx+Gu.sub.x.sup.n-3u.sub.xx.sup.3+Hu- .sub.x.sup.n-2u.sub.xxu.sub.xxx+Iu.sub.x.sup.n-1u.sub.xxxx (Eq. 2)

where u is the displacement, .tau. is a resealed time, n is the nonlinear exponent found in Eq. 1 and the explicit expression of the parameters I, H, G can be found in Porter, M. A.; Daraio, C.; Herbold, E. B.; Szelengowicz, I.; Kevrekidis, P. G. "Highly nonlinear solitary waves in phononic crystal dimers" Physical Review E, 77, 015601(R), 2008.

[0038] The solution for Eq. 2, describing the shape and properties of the highly nonlinear solitary waves, from direct integration is of the form shown in Eq. 3 below:

u = v = B cos 2 n - 1 (.beta. .xi.) , where B = (.mu. [.beta. 2 s (s - 1)]) 1 / n - 1 , .beta. = .sigma. (1 - .eta.) 2 and s = pI . (Eq . 3) ##EQU00001##

[0039] The generality of the highly nonlinear wave equation shown in Eq. 2 is given by the fact that it includes also the linear and weakly nonlinear regimes of wave propagation. These regimes can be extrapolated by adding an initial prestrain (precompression) to the system. Its solution demonstrates that in a highly nonlinear medium only two harmonics contribute to a stationary mode of propagation of the periodic signal. The solitary shape, if the initial prestrain .xi..sub.0 is approaching 0, can be taken as one hump of the periodic solution provided by Eq. 3 with finite wave length equal only to five particle diameters in the case of a Hertzian granular system. In analogy with the KdV solitons, the highly nonlinear solitary waves are supersonic, which means that their phase velocity is larger than the initial sound velocity (c.sub.0) in the nonlinear medium (especially in the case of an uncompressed system, in which the c.sub.0=0). For granular chains composed by spherical particles, the speed of the solitary wave V.sub.s as nonlinear function of the maximum particle dynamic strain can be expressed as shown in Eq. 4:

V s = 2 5 c .xi. m 1 / 4 = 0.6802 (2 E a .rho. 3 / 2 (1 - v 2)) 1 / 3 F m 1 / 6 , (Eq . 4) ##EQU00002##

where F.sub.m is the maximum dynamic contacts force between the particles in the discrete chain.

[0040] The relationship shown in Eq. 4 may provide for applications in the field of dynamics and acoustic properties of materials. Such waves, as predicted by the theory and validated numerically and experimentally, have tunability characteristics. By changing the mechanical and/or the geometrical properties of the high nonlinear medium supporting the formation of HNWs, the shape and the properties of the traveling pulse can be tuned. In other words, the properties of the nonlinear waves in the highly nonlinear media can be "engineered" for a specific application. These "controllable" waves may then be used as new boundary conditions in various structures for testing. It may also be desirable to generate a train of nonlinear waves rather than a single nonlinear pulse.

[0041] The analytical expression for the tunability of the solitary waves speed in a Hertzian system derived from the presence of added precompression and obtained from the discretization of the particles in the chain, is expressed as shown in Eq. 5 below:

V s = 0.9314 (4 E 2 F 0 a 2 .rho. 3 (1 - v 2) 2) 1 / 6 1 (f r 2 / 3 - 1) { 4 15 [3 + 2 f r 5 / 3 - 5 f r 2 / 3] } 1 / 2 . (Eq . 5) ##EQU00003##

where F.sub.0 represents the static prestress (precompression) added to the system, f.sub.r=F.sub.m/F.sub.0 and F.sub.m is the maximum contacts force between the particles in the discrete chain.

[0042] The dependence of the solitary wave properties on the materials parameters is shown in Eq. 4 for a non-prestressed system and in Eq. 5 for a prestressed system. Also note that, with HNSWs, the system is size independent but sensitive to the presence of periodic heterogeneities in the chain. Therefore, the solitary waves may be scalable to various sizes, according to the needs of each specific application.

[0043] According to Eqs. 4 and 5, the tunability of the HNSWs can be achieved by varying one or more parameters of the nonlinear medium. For example, increasing the particle size of the highly nonlinear medium increases the wavelength and the wave speed and amplitude decrease. This tunability provides the possibility of reducing or eliminating the electronic equipment, such as function generators, necessary to excite stress waves of a given shape and wavelength. Therefore, embodiments of the present invention may reduce some of the power demands in ultrasonic actuation needed by prior art systems and may allow the use wireless technology instead of tethered technology known in the art. In addition, the high-sensitivity of wave amplitude and wave speed to the state of stress state in highly nonlinear material may also allow for improvements in the estimation of applied stress over that obtained by conventional acoustoelastic methods.

[0044] Embodiments of the present invention also allow for the use of particles having morphology different than the one described by the classical Hertzian shape (n=1.5), which can add another element to the tunability, that is by varying n in Eq. 1 the wavelength (and, therefore, the signal's frequency) will vary significantly. Further, a HNW or HNSW traveling in a system composed of alternating short chains of hard and soft beads (that can be interpreted as defects) or in any periodic heterogeneous system will induce significant changes in the properties of the traveling pulse. Systems composed of randomized assemblies of particles, such as chains including particles of different materials, masses and diameters in a disordered and quasi-disordered configuration, present thermalization phenomena that induce pulse decomposition and excitation of higher frequency modes.

[0045] The use of solitary waves for defect and impurity detection in granular media is discussed in Sen, S., Manciu, M., and Wright, J. D., "Solitonlike Pulses in Perturbed and Driven Hertzian Chains and Their Possible Applications in Detecting Buried Impurities," Phys. Rev. E, 57, no. 2, 2386-2397 (1998) and in Hong, J. & Xu, A., "Nondestructive identification of impurities in granular medium." Appl. Phys. Lett., 81, 4868-4870 (2002). Solitary waves have been demonstrated to be sensitive to the granular materials properties, such as elastic modules, and applied stress and the dependence of the velocity and shape of the backscattered signal on the presence of light and heavy impurities in a granular chain have also been noted. Highly nonlinear solitary pulses have been studied numerically and experimentally in various one-dimensional highly nonlinear systems assembled from chains of stainless-steel, glass, brass, nylon, polytetrafluoroethylene (PTFE) and Parylene coated steel beads. As predicted by the theoretical formulation, the numerical and experimental validation showed a significant difference in the speed and amplitude of the supported solitary waves as a function of the materials parameters.

[0046] The equations discussed above generally apply to HNSWs. However, embodiments of the present invention may rely upon the generation and/or detection of HNWs, treating the generation and/or detection of HNSWs as just a special case of HNWs. A schematic representation of a system for production and/or detection of HNWs is shown in FIG. 1A. In FIG. 1A, a chain 501 of particles or beads 505, 507, 509 is positioned between stays 603. By impinging the first particle 505 into the second particle 507, a HNW is generated (however, the generated HNW may stabilize into a HNSW). In this configuration, the first particle 505 may be considered as a striker particle. The wave propagates as long as the particles 505, 507, 509 stay in contact. Wavelength, speed, and amplitude of the wave can be tuned by selecting a desired combination of chain size (diameter and number of particles), particle material, and pre-compression on the particles. Some of the particles 509 may have embedded piezoelements or other detection apparatus that can be used to monitor the propagation of HNWs within the chain 501. The system shown in FIG. 1A can also be used for the detection of HNWs by coupling the system to a material or structure and using the detector particles 509 with the piezoelements to detect the waves.

[0047] FIG. 1B illustrates a detector particle 509 with an embedded piezoelement to detect HNWs. The detector particle 509 comprises particle halves 62 and a piezoelement 64 sandwiched between the two halves 64. The piezoelement 64 is preferably attached to the two halves 62 with an adhesive layer 66, where the adhesive layer 66 may comprise epoxy or other adhesive material. The particle halves 62 may be notched to allow for leads 65 from micro-miniature wiring associated with the piezoelement 64 to be embedded within the particle 509. The piezoelement 64 may have the wiring of the opposite faces of the piezoelement or in the same face by using a wrap around electrode and lead attachment. Preferably, the piezoelement 64 is calibrated to increase the accuracy of wave detection.

[0048] Systems for producing or detecting HNWs are depicted in FIGS. 2A and 2B. FIG. 2A shows a three dimension view of an actuating and or sensing apparatus. As shown in FIG. 2A, four rods 30 are used to confine a chain of beads 44 that are used for the creation of highly nonlinear pulses for transfer to an element 20 or material to be tested. FIG. 2B shows a vertical cross-section of an apparatus similar to the one depicted in FIG. 2A where the four rods are replaced by a hollow cylindrical container 32 within which a chain of beads 44 is constrained. As discussed above, it may be useful to apply precompression for tuning the highly nonlinear waves. In FIG. 2A, element 50 depicts a system that may be used to apply static precompression. Element 50 may comprise a levitating ring magnet, a system to suspend controlled weights, a screw/load-cell controlled prestraining device, some other element or system that can compress the chain of beads 44, or some combinations of the elements and systems listed herein. As shown in FIG. 2B, a magnetic bead (or a bead holding suspended weights) 42 may be placed on top of the chain of beads 44 to allow for the application of static precompressive force. FIG. 2B also shows an outer holder 54 for handling and anchoring the hollow cylindrical container 30 on the element 20 or structure to be tested.

[0049] The constrained chain of beads 44 shown in FIGS. 2A and 2B may serve to produce or detect HNWs. For the production of such waves, a striker 40 may be used to initiate the formation of the HNW in the chain of beads 44. The striker 40 may be actuated through the use of an electromagnet 46 to move the striker 40 to strike the chain of beads 44. For example, the striker 40 may comprise a stainless steel ball lifted and released through an alternating magnetic field created by the electromagnet 46. The magnetic bead 42 shown in FIG. 2B may also serve as a means by which the chain of beads 44 are struck to produce pulses. A magnetically or an electro-magnetically controlled apparatus may be capable of generating pulses at frequencies greater than 20 kHz. Alternative embodiments may use a different activation mechanism such as a spring loaded system or a compressed air loaded system.

[0050] FIG. 3A is a schematic diagram representing the wave propagation of HNWs in a bulk highly nonlinear, weakly nonlinear or linear medium. A highly nonlinear pulse generator 10 (also referred to herein as a highly nonlinear actuator/exciter) generates a single or a train of highly nonlinear waves 14 that is directed into the element 20 or structure under test. FIG. 3A shows the propagation of the wave 14 through the element 20, which may comprise a bulk highly nonlinear, weakly nonlinear or linear medium. The propagating wave within the medium under testing may comprise linear stress waves and/or highly non linear waves. An output pulse 16 is received by a highly nonlinear receiver 12. FIG. 3B shows the generation of the single HNW 14 by the actuator 10 in the element 20, which may comprise a waveguide structure made of highly nonlinear, weakly nonlinear or linear medium. In FIG. 3B, the actuator 10 for HNWs is used also as sensing element for pulses 18 reflected by the waveguide edges and or defects.

[0051] One embodiment of the present invention comprises a method and system where a highly nonlinear actuator is used in combination with a classical receiver (such as an accelerometer, laser interferometer, piezogauge or other detectors known in the art). FIG. 4 depicts a system with this configuration. In FIG. 4, a highly nonlinear actuator/exciter 10 provides pulses to the element 20 that is undergoing testing with a potential defect 489. Element 20 may have a bulk or waveguide geometry and may comprise a highly nonlinear, weakly nonlinear or linear medium. The nonlinear actuator/exciter 10 has a striker particle 40 to initiate the formation of the HNW in the actuator 10. A first piezogauge 481 detects signals entering the element 20 under testing and a second piezogauge 482 detects the output signal after traveling in the tested element 20. A computer 90 may be used to process and store data to provide an analysis of the characteristics of the measured element 20. One or more calibrated piezogauges 64 disposed within elements of the actuator 10 may be used to detect the HNW propagating within the actuator/exciter 10 to provide the ability to additionally control or tune the actuator/exciter 10 to produce an HNW with desired characteristics.

[0052] Another embodiment of the present invention comprises a method and system where a classical impact echo/tap testing hammer (or other such methods or apparatus known in the art) is used in combination with a highly nonlinear receiver. FIG. 5 depicts a system with this configuration. In FIG. 5, a classical or a modally tuned hammer 96 is used to provide pulses to the element 20 or structure under test. Element 20 may have a bulk or waveguide geometry and may comprise a highly nonlinear, weakly nonlinear or linear medium. Typically, the hammer 96 may contain a piezogauge to detect and/or control pulses generated by the hammer 96. A nonlinear receiver 12 is coupled to the element 20 under test to receive pulses transmitted through the element 20 under test. The nonlinear receiver 12 may also be coupled to a piezogauge 482 which receives the HNW that has propagated through the nonlinear receiver 12. The nonlinear receiver 12 may also have one or more piezogauges 64 disposed within elements of the receiver 12 to detect the HNW propagating within the receiver 12. The receiver piezogauge 64 may be used in addition to or as an alternative to the piezogauge 482 to provide data on the characteristics of the element 20 under test. The receiver piezogauge 64 may also provide the capability to tune the response of the nonlinear receiver 12. A computer 90 may be used to collect and store data from the piezogauges 64, 482 and the hammer 96 to provide an analysis of the element or structure under test.

[0053] Still another embodiment of the present invention comprises a method and system where a highly nonlinear actuator is used in combination with a highly nonlinear receiver. FIG. 6 depicts a system with this configuration. In FIG. 6, a highly nonlinear actuator/exciter 10 provides pulses to the element 20 that is undergoing testing. As discussed previously, the actuator 10 may have one or more piezogauges 64 embedded within elements of the actuator 10 for HNW detection. A nonlinear receiver 12 is coupled to the element 20 under test to receive either highly nonlinear or linear pulses or a combination of both transmitted through the element 20 under test. Element 20 may have a bulk or waveguide geometry and may comprise a highly nonlinear, weakly nonlinear or linear medium. As discussed previously, the nonlinear receiver 12 may also have one or more piezogauges 64 disposed within elements of the receiver 12 to detect the HNW propagating within the receiver 12. The nonlinear receiver 12 may also be coupled to a piezogauge 482 which receives the HNW that has propagated through the nonlinear receiver 12 from the element 20 under test. A computer 90 may be used to collect and store data from the piezogauges 64, 482 to provide an analysis of the element or structure under test.

[0054] FIG. 7 is a flow chart showing steps of a method for performing nondestructive evaluations and structural health monitoring according to an embodiment of the present invention. In block 105, a striker is used to generate a pulse. In block 106, the pulse is coupled to a chain of beads serving as a transmitter for the formation of a HNSW. Block 107 depicts the detection and measurement of that wave within the transmitter and/or at the interface between the transmitter and the material or structure to be tested. Block 108 represents the propagation of the HNSW, or the propagation of linear bulk or linear guided waves within the material or structure to be inspected. Block 109 depicts the reception of one or more of those waves by a chain of beads with embedded piezoelement(s) acting as a receiver and the detection of the highly nonlinear pulses within the receiver and/or at the interface between the receiver and the material or structure under test. The signal detected prior to the material or structure under test and the signal detected after the material or structure under test are digitized at block 110 and measurements of the pulses made at block 111. Pulse measurement block 111 may include linear waves detected at the interface between the receiver and the material/structure under test. These nonlinear pulse measurements can then be used to characterize the material measured by an inverse approach, as shown in block 112, and/or detect damage within the structure or material, as shown in block 113.

[0055] FIG. 8 is a flow chart showing steps for characterizing a material by using an inverse approach according to an embodiment of the present invention. In FIG. 8, block 114 represents the measurements of highly nonlinear pulses, such as those provided as shown in block 111 in FIG. 7. Calculations are then performed to determine the characteristics of the measured pulse or pulses as shown in block 115. Block 117 shows the collection of data related to the elastic properties of a large class of materials. Block 118 shows the calculation of a theoretical model of wave pulse propagation for a selected material type. Decision block 116 shows the comparison of measured pulse characteristics as provided by block 115 with theoretical characteristics as provided by block 118. If the measured and theoretical pulse characteristics are the same or nearly the same, block 120 shows that the properties of the measured material or structure can be characterized based on the measured pulses. If the measured and theoretical pulse characteristics do not sufficiently match, the differences can be provided to a digitizer 119 and then used to select a different material type for calculation of a theoretical model in block 118.

[0056] FIG. 9 is a flow chart showing steps for determining whether a material or structure has any damage based on various excitations. In FIG. 9, block 121 represents the acquisition of measured pulsed data, such as that shown in block 111 in FIG. 7 and, for example, acquired by one of the methods depicted in FIGS. 4, 5 and/or 6. Block 122 shows the digital signal processing that may be performed on the pulse data to extract time domain related characteristics, frequency domain related characteristics, joint time-frequency domain characteristics, or other mathematical representations of the measured pulse data. Block 123 represents the calculations that may be performed to extract features of interest that may be used to identify and/or characterize damage. These features may be then used to construct a damage index vector, as shown in block 124, that may have one or more parameters related to damage identification. A supervised learning algorithm (as shown in block 125) or an unsupervised learning algorithm (as shown in block 126) may then be used to process the damage index vector and provide information as to the presence of defects or damage within the measured material or structure.

[0057] FIG. 10 illustrates the application of a HNW to a damaged structure and propagation of the excited pulse through the structure and a test setup to detect the damage. In FIG. 10, a nonlinear actuator 10 forms and applies a HNW 14 to the element 24 under test. Element 24 can be a bulk, waveguide or semi-infinite structure made of highly nonlinear, weakly nonlinear, or linear medium. As depicted in FIG. 10, the element 24 may comprise a panel, plate, pavement, tile, flooring, etc. Sensors 48, such as accelerometers, laser interferometers, piezogauges, pressure sensors or other such detectors, detect and measure the propagation of the pulses through the element. The presence of a crack/void/deformation 22 in the element is expected to alter the amplitude and shape of the waves detected in output signals from the detectors 48. Analysis of the data obtained from the sensors should allow a user to locate and characterize the defect 22.

[0058] Embodiments of the present invention may also be used to detect defects in cylindrical waveguides made of highly nonlinear, weakly nonlinear, or linear medium. For example, FIG. 11 depicts a seven-wire steel strand 261 and a damaged seven wire steel strand 263. Such wire strands are widely used parts in prestressed concrete and cable-stayed suspension bridges. In FIG. 11, a nonlinear actuator 10 is used to apply the HNW and a nonlinear receiver 12 is used to detect the HNW. In the damaged strand 263, the presence of a prestress/temperature induced stress/strains and/or crack/void/deformation (as represented by the void 22) is expected to alter the amplitude and shape of the solitary waves detected by the nonlinear receiver 12. Alternative embodiments of the present invention allow for the detection of defects within cable configurations other than stranded steel.

[0059] FIGS. 12A and 12B show experimental results where HNWs-induced pulses are propagated within a steel rod. In FIG. 12A, pulses were generated with a variable number (n) of beads into a chain of stainless steel beads. In FIG. 12B, pulses were generated by impacting a miniature hammer and by using n=10, 30 of HNW-inducing beads. As can be seen from FIGS. 12A and 12B, the time domain characteristics of the pulses change with the number of beads used to induce the HNW, indicating the tunability of the HNW actuator.

[0060] Experimental data shows that a HNW can be excited in a damaged and undamaged structure. The pulse detected after traveling in a damaged structure will differ from one detected after propagating through an undamaged structure. FIGS. 13A and 13B show experimental curves obtained for a test setup as shown in FIG. 4, where the element 20 under test is a steel rod. FIG. 13A depicts data obtained from positioning 4.76 mm diameter beads on a pristine steel rod, while FIG. 13B depicts data obtained from positioning 4.76 mm diameter beads on a damaged steel rod. Sensors were positioned in one of the central beads composing the chain (curve labeled "bead sensor" and corresponding to element 64 in FIG. 4), at the interface (corresponding to element 481 in FIG. 4) and at the base below the steel rod (corresponding to element 482 in FIG. 4). The impulses were generated by dropping a 0.45 g steel bead from a height of 3 cm on the top particle of the chain. FIGS. 14A and 14B show experimental curves obtained for a test set up similar to that shown in FIG. 4 where the element 20 under test is again a steel rod. However, sensors were positioned only at the interface and at the rod's base. FIG. 14A depicts data obtained from positioning 2.38 mm diameter beads on an undamaged steel rod and FIG. 14B depicts data obtained from positioning 2.38 mm diameter beads on a damaged rod. The impulses were generated dropping a 0.45 g steel bead from a height of 3 cm on the top particle of the chain.

[0061] As discussed above, precompression may also serve to tune the HNW provided by a nonlinear actuator. FIGS. 15A, 15B, 16A and 16B illustrate the effect that precompression may have. FIG. 15A depicts time data obtained from positioning 20 vertically aligned stainless steel particles on top of a 4.76 mm diameter steel rod with added static precompression (F.sub.0=2.38 N). The test setup was similar to that shown in FIG. 4, where sensors were positioned in one of the central beads composing the chain (curve labeled "bead sensor" and corresponding to element 64 in FIG. 4), at the interface (corresponding to element 481 in FIG. 4) and at the base below the steel rod (corresponding to element 482 in FIG. 4). FIG. 15B shows time data obtained with a similar set up using a damaged rod. FIG. 16A shows intensity verses frequency data obtained from measurements made from the pristine rod, while FIG. 1 6B shows intensity versus frequency data obtained from the damaged rod.

[0062] An embodiment of the present invention may comprise a method and system for automated evaluation and monitoring of pavements, railroads, floor spaces and other such structures. FIG. 17 is a schematic view of such an embodiment. In FIG. 17, a trolley 80 has both a nonlinear actuator 10 and a nonlinear receiver 12 mounted on it. The nonlinear actuator 10 and a nonlinear receiver 12 are both mounted in a fashion that allows them to contact the structure 20 under test. In operation, the nonlinear actuator 10 provides highly nonlinear pulses and the nonlinear receiver 12 detects the highly nonlinear pulses. As indicated above, alternative embodiments may use classical impact methods known in the art (such as an impact hammer) instead of the nonlinear actuator 10 to provide pulses for detection by the nonlinear receiver 12. Other embodiments may use the nonlinear actuator 10, but the pulses from the actuator 10 may be detected by classical detection methods or apparatus instead of the nonlinear receiver 12.

[0063] In the system depicted in FIG. 17, the computer 90 may provide for control over the nonlinear actuator 10 and the nonlinear receiver 12 and also control the motion of the trolley. Signals to and from both the nonlinear actuator 10 and the nonlinear receiver 12 may be coupled to a data collection station 70 that may be coupled, either wirelessly or with a wired connection, to the computer 90. For example, the data collection station may comprise a unit from National Instruments utilizing PXI technology running LabView.RTM. or analogous hardware/software. The computer 90 may comprise a laptop computer which could then be configured to form a client-server Ethernet link with the data collection station 70. The data collection station 70 may be configured to control the generation of test pulses by the nonlinear actuator 10, acquire signals from the nonlinear receiver 12, process the signals to limit noise, and produce a real-time quality index for the monitored structure 20. The computer 90 may then be used to start and stop the acquisition, modify the pulse and pulse processing settings, monitor the results in real-time, and provide report windows.

[0064] The system depicted in FIG. 17 may provide a user the ability to exploit HNW induced pulses propagating across and along the thickness of the structure 20 and within the structure 20 itself. While FIG. 17 only shows a single actuator 10/receiver 12 pair, multiple actuator/receiver pairs may be deployed to form a grid that covers large sections of the structure 20 at once. This may speed up the rate at which the structure 20 can be inspected and also improve the quality of the inspection.

[0065] The foregoing Detailed Description of exemplary and preferred embodiments is presented for purposes of illustration and disclosure in accordance with the requirements of the law. It is not intended to be exhaustive nor to limit the invention to the precise form or forms described, but only to enable others skilled in the art to understand how the invention may be suited for a particular use or implementation. The possibility of modifications and variations will be apparent to practitioners skilled in the art. No limitation is intended by the description of exemplary embodiments which may have included tolerances, feature dimensions, specific operating conditions, engineering specifications, or the like, and which may vary between implementations or with changes to the state of the art, and no limitation should be implied therefrom. This disclosure has been made with respect to the current state of the art, but also contemplates advancements and that adaptations in the future may take into consideration of those advancements, namely in accordance with the then current state of the art. It is intended that the scope of the invention be defined by the Claims as written and equivalents as applicable. Reference to a claim element in the singular is not intended to mean "one and only one" unless explicitly so stated. Moreover, no element, component, nor method or process step in this disclosure is intended to be dedicated to the public regardless of whether the element, component, or step is explicitly recited in the Claims. No claim element herein is to be construed under the provisions of 35 U.S.C. Sec. 112, sixth paragraph, unless the element is expressly recited using the phrase "means for . . . " and no method or process step herein is to be construed under those provisions unless the step, or steps, are expressly recited using the phrase "comprising step(s) for . . . "