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(54) Title: PULSE TRAPPING COMPOSITE GRANULAR MEDIUM AND METHODS FOR FABRICATING SUCH MEDIUM

(57) Abstract: A composite granular structure, which enables forced energy confinement and disintegration of impulses propagating in a laminar granular medium and fabrication methods for said structure. The granular structure comprises an array of composite chains of alternating high-modulus, rigid beads and lower modulus, soft beads in a supporting matrix.

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PULSE TRAPPING COMPOSITE GRANULAR MEDIUM AND METHODS FOR FABRICATING SUCH MEDIUM

FIELD OF THE INVENTION

The present invention relates to shock absorption devices, in particular, devices composed of granular structures.

BACKGROUND OF THE INVENTION

Explosions, blasts, impacts and any wave propagation in the form of a drastic increase of pressure are common in our everyday life. From impacts generated by the dropping of a device, to detonation shocks from explosives, there is a vast need for shock-attenuating barriers and protectors adaptable to different media of pulse propagation.

Granular beds composed of iron shot (waste from the metallurgical plants), sand bags and concrete have been successfully used as shock-mitigating protectors for example in the design of explosive chambers reducing the amplitude of shock wave generated by contact explosion. In the past, the design of shock protectors focused mainly on the enhanced energy dissipation obtainable by layered systems or by the friction in granular media. A more efficient way of protecting materials from the shock may be realized, according to the invention disclosed here, through the confinement of an impulse in a specially arranged region of the granular medium.

Granular matter, common in our everyday life, has many known applications but it presents fundamental difficulties in the understanding of its intrinsic dynamic properties due to the strong nonlinearity and complex contact-force distributions. Their three dimensional structural features include filamentary force chains which may be relevant to characterization of the behavior of other matters such as in a glassy state.

Strongly nonlinear systems, for example, one-dimensional chains of beads, exhibit a very unique wave dynamic behavior, especially at the interface between two different granular systems or at the interface of granular media and solid matter. See chapter 1 by V.F. Nesterenko, *Dynamics of Heterogeneous Materials*, (Springer-Verlag, NY, 2001).

The strongly nonlinear behavior in a chain of elastic spherical beads arises from the nonlinearity of the Hertzian contact interactions between the particles composing the system and results in a power-law type dependence of the compressive force (F) on displacement (δ) ($F \propto \delta^{3/2}$) combined with zero tensile strength. In the case of zero or very weak precompression (i.e. "sonic vacuum" type systems, SV) the corresponding wave equation supports a qualitatively new solitary wave. A peculiar property of the granular media derives from the possibility of "tuning" the type of stationary solution produced by the system by varying the precompression acting on the chains. This allows "choosing" the regime of wave propagation or the reflection from the interfaces of two SVs according to the needs for each specific application.

It has been discovered (V.F. Nesterenko, *Dynamics of Heterogeneous Materials*, Chapter 1 (Springer-Verlag, NY, 2001), page 76-77) that the passage of a solitary wave through the interface of two "sonic vacui" (SV) type systems from a region of higher elastic modulus (or higher mass) to a region of lower elastic modulus (or lower mass) results in the impulse disintegration into a train of solitary pulses. In the zero or weakly precompressed case, the number of pulses composing the train is proportional to the ratio of the difference in the mass of the particles at the two sides of the interface. In this case, no reflected wave from the interface is observed propagating back into the stiffer region. Vice versa, when the solitary wave in SV passes from the softer (lower elastic modulus) region to the stiffer region, it divides its energy into 2 portions: one propagating through the interface, and the other reflected back into the softer material. In this case, no impulse disintegration after the interface is observed. This behavior was first suggested as a technique for nondestructive identification of impurities in a granular medium (with implications in the analysis/detection in geological or biological fields), then later as a way of protecting materials. See Sen, M. Manciu and J.D. Wright, Phys. Rev. E, 57, 2386 (1998); J. Hong and A. Xu, Applied Physics Letters, 81, 4868 (2002); J. Hong, Phys. Rev. Lett. 94, 108001 (2005).

At present the protection of everyday devices and objects from different kind of impacts is becoming of primary concern for safety, communication, shielding, and security purposes. Thus, there is a need for novel, tunable and efficient shock protectors, scramblers and absorption layers adaptable for different applications.

SUMMARY OF THE INVENTION

The invention discloses a unique, vertically aligned, composite granular structure which enables a forced energy confinement and disintegration of impulses propagating in a strongly nonlinear laminar granular medium. Viable fabrication methods for assembling such a novel structure in a practical, three-dimensional configuration are also described. The shock-energy-trapping medium consists of an array of composite chains of alternating ensembles of high-modulus beads such as made of stainless steel vs orders of magnitude lower modulus beads such as PTFE (polytetrafluoroethylene) spheres in a supporting matrix. The chains function as pulse-energy confiners and their trapped energy is slowly leaked in the form of weak and harmless, separated pulses over an extended time period. This significant pulse-disintegrating effect is especially pronounced on a specific grouped assembly within the chains and can be enhanced by superimposed force. This device can be utilized as an efficient protector for technological and security applications.

BRIEF DESCRIPTION OF THE DRAWINGS

The advantages, nature and additional features of the invention will appear more fully upon consideration of the illustrative embodiments described in the accompanying drawings. In the drawings:

FIG. 1(A) and (B) schematically illustrate an exemplary pulse trapping device comprising three-dimensionally pre-configured chains of soft and rigid beads according to the invention;

FIG. 2 (A) (B) and (C) schematically illustrate exemplary alternative embodiments of pulse trapping devices with mechanical pre-stress according to the invention. (2A) shows a portion of the cross-sections of the granular medium in the absence of pre-stress on the chain of beads, (2B) illustrates a case of engineered, locked-in internal compressive pre-stress, (2C) shows a case of externally applied mechanical compressive pre-stress.

FIG. 3 (A) and (B) schematically illustrate other alternative embodiments of pulse trapping devices with magnetically induced pre-stress according to the invention. (3A) shows a portion of the cross-sections of the granular medium in which the pre-stress is induced by external electromagnetic field on magnetic beads (upper magnetic beads not shown), (3B) illustrates a case of compressive pre-stress introduced by magnets.

FIG. 4 (A) through (G) schematically illustrate an exemplary inventive method for making the shock-disintegrating granular structure;

FIG. 5 (A) through (D) show an alternative inventive method for making the shock-disintegrating granular structure using a magnetic holding technique;

FIG. 6 is a flow diagram illustrating the exemplary steps for making the inventive tunable assembly;

FIG. 7 shows an alternative way of filling the vertical channels with different types of soft or rigid beads. Continuous (or semi-continuous) supply of rigid beads (such as stainless steel balls) vs soft beads (such as Teflon balls) can be made from the bottom through a reservoir, or a vertical channel array, or a tube. The upper structure (the final protector), can be moved sideways back and forth so that the two types of beads can be moved up by a piston-like structure in a desired manner. The beads can also be continuously supplied, for example, using a bead-supplying-tube actuated by a pneumatic mechanism.

FIG. 8 (A) (B) and (C) show experimental data on solitary pulse trapping induced in an exemplary inventive device. (8A) shows schematic diagrams of the stainless steel and PTFE beads geometrical arrangements used for testing. (8B) shows experimental results corresponding to the sensors indicated in (8A). (8C) shows experimental results corresponding to (8B) with magnetically induced superimposed force. The y-axes scale is 1 N;

FIG. 9 (A) and (B) show experimental and numerical data on solitary pulse trapping induced in an exemplary inventive device. (9A) shows experimental results obtained by the impact by an Al_2O_3 (0.47 g) striker with a velocity of 0.44 m/s. (9B) shows numerical analysis corresponding to (9A). The y-axes scales for the curves have been adjusted to ease the comparison of the pulse details, amplitudes of the leading pulses are provided in the panels;

FIG. 10 (A) and (B) show experimental and numerical data on shock pulse trapping induced in an exemplary inventive device. The curves from the top correspond to the sensor placed in the 4th steel particle from the top, the 11th beads (3rd particle in the first PTFE section of the chain), the 22nd (3rd particle in the second PTFE section of the chain) and at the bottom wall correspondingly. The y-axes scale is 1 N. (10 A) shows experimental results obtained by the impact by an Al_2O_3 rod (63 g) striking with a velocity of 0.44 m/s. (10B) shows numerical data corresponding to (10A).

FIG. 11 (A) and (B) show alternative protecting devices consisting of layered materials with different elastic properties fabricated using pre-patterned (Fig. 11(A)) or pre-grooved (Fig. 1(B)) configurations.

FIG. 12 shows examples of device applications.

FIG. 13 describes a three-dimensional phononic crystal, as a focus-adjustable acoustic lens; and,

FIG. 14 schematically illustrates the use of tunable phononic crystals for brain surgery.

It is to be understood that the drawings are for purposes of illustrating the concepts of the invention and are not to scale.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the drawings, FIG. 1(A) and (B) schematically illustrate, according to the invention, an exemplary composite granular structure capable of forced energy confinement and disintegration of impulses propagating in a strongly nonlinear laminar granular medium. It is composed of a matrix support material with an array of vertical holes, FIG. 1(A), which contain an array of laminar chains comprising alternating grouped sections of elastically "soft" beads **11** and "rigid" beads **10**, as illustrated in FIG. 1(**B**). The matrix material with an array of vertically aligned pores can be derived, for example, from a solid material such as an anodized alumina (AAO) or photo-lithographically patterned silicon or metal substrate. The matrix can alternatively be a softer material, for example, a polymer material. The array of vertical pores in the polymer can be made by a number of different ways, for example, by pouring an uncured elastomer, epoxy, or gel type meterial onto a bed-of-nails structure, with the bed-of-nails portion removed later after curing of the polymer by pulling out from the cured composite structure. The nails can be pre-coated by lubricant material such Teflon in order to make the pulling out of the bed-of-nails easier. The vertical pores are then filled with spherical nanoparticles of different materials.

In Fig. 1(**B**), the vertical holes are omitted and not shown for the sake of showing the beads in a greater detail. The beads are defined here as spherical, oval, cylindrical, tube-shaped, rectangular or other shaped materials which do not have a flat top or bottom surface so that their contact with another bead above or below induces an alterable surface area on application of vertical elastic stresses.

"Soft" beads **11** are defined as a material with relatively low Young's elastic modulus values (E) in the range of 0.1 – 5000 MPa preferably in the range of 100-1000 MPa. Typical example materials suitable for use as the soft bead material includes Teflon (polytetrafluoroethylene, also known as PTFE) (nominal E=400-600 MPa), elastomers (E=0.2 – 3000 MPa pascals), gels (E=0.1 – 2 MPa), polyethylene (E=100 – 1000 MPa).

"Rigid" beads **10** are defined as a material with relatively high Young's elastic modulus values (E) in the range of 1 – 400 GPa. Some exemplary materials suitable as the rigid beads in the invention structure includes steels (E~200GPa), aluminum and their alloys (E~70 GPa), Cu and their alloys (E~140GPa), Ti and their alloys (E~110 GPa), molybdenum and alloys (E~230GPa), tungsten and alloys (E~310 GPa), uranium and alloys (E~100 GPa). Ceramic materials such as diamond (E~1000 GPa), oxide ceramics such as aluminum oxide (E~390GPa), titanium oxide (E~280 GPa), zirconium oxide (E~ 160 – 241 GPa), silicon oxide (100 GPa), carbide ceramics such as tungsten carbides (E~ 450 -650 GPa), titanium carbide (350 GPa), nitride ceramics such as titanium nitride (E~600 GPa), tantalum nitride (E~576 GPa), etc. may also be used as the rigid bead material.

The difference in the elastic moduli between the soft beads and the rigid beads is at least a factor of 10, preferably a factor of 100. The chains of beads comprise alternating ensembles of from at least 1 to about 24 soft beads in a row and at least 1 to about 24 rigid beads in a row. Preferably, there are at least 2 beads of each in a row.

Beads **10** and **11** are inserted into vertical pores **13** according to a specifically designed sequence of chains of at least two types of soft vs rigid materials into a pre-patterned matrix **12** containing a desired number of guiding holes and length. The particle diameter can be chosen to scale the system according to the threat and for this purpose also different elastic materials can be selected. While the examples shown here refer to a mixture of one soft and one rigid bead materials, the invention allows other more complicated combinations such as, e.g., 1-4 kinds of soft bead materials and 1-4 kinds of rigid bead materials. The support matrix **12**, or guiding container, can be made of many different types of materials such as plastics, wood, aluminum or other metals, PTFE (polytetrafluoroethylene, commonly known as Teflon), etc. It can be manufactured by moulding or casting of materials into a container having array of pre-arranged pins, or can be machined from a bulk piece of material by drilling holes of the desired diameters and lengths. Other fabrication techniques such as lithographic etching, laser drilling, etc. may also be utilized.

The desired size of the beads is in the range of 0.001 – 1000 mm, although these values need to be adjusted according to the desired applications. While vertical alignment of the beads is preferred, a slight off-axis alignment is acceptable with the maximum variation off the vertical axis of less than 30 degrees.

The added pre-stress present in the granular medium influences the pulse disintegrating behavior, as will be evident by the further description of data and interpretations later in this application. Therefore, the invention calls for an optional introduction of such a pre-stress in order to provide a tunability of the pulse disintegrating characteristics.

FIG. 2 schematically illustrates exemplary alternative embodiments of pulse trapping devices with mechanical pre-stress according to the invention. For the sake of simplicity, the vertical holes are not shown. Also, not all the beads comprising the granular medium of FIG. 1 are shown in FIG. 2, for example, the upper ensemble of rigid beads are not shown in FIG 2(A)-(C). FIG 2(A) shows a portion of the cross-sections of the granular medium in the absence of pre-stress on the chain of beads, which is basically a portion of FIG 1(**B**) structure.

FIG. 2(**B**) illustrates a case of engineered, locked-in internal compressive pre-stress. Such a permanently locked-in internal compressive pre-stress can be introduced if the matrix material is allowed to move into the gaps between adjacent beads, for example, if an elastomer or epoxy is allowed to cure with the beads in a vertically aligned state. Such a structure of FIG.1(**B**) can be fabricated using magnetic alignment technique for ferromagnetic particles in elastomer matrix. See articles by S. Jin et al, "New Z-Direction Anisotropically Conductive Composites", *J. Appl. Phys.* ***64***, page 6008 (1988), and "Optically Transparent Electrically Conductive Composite Medium", *Science* ***255***, page 446 (1992). The rigid beads can be selected to be ferromagnetic material such as Ni, Fe, Co or their alloys. The soft beads can be constructed using such a ferromagnetic core coated with low modulus material (e.g., Ni particles coated with epoxy or Teflon), so that both soft and rigid beads respond to the z-direction applied magnetic field and self align into parallel chain-of-spheres configuration. Since the thermal contraction coefficient of elastomer or epoxy is much higher than the metal, and since there is a polymerization shrinkage, a locked-in, vertical compressive stress is obtained in the composite of FIG. 2(**B**) when the elastomer or epoxy matrix is cured and solidified at ~120°C-150°C and cooled to room temperature.

A method for manufacturing a three-dimensional pulse trapping device described above comprises:

i) mixing rigid magnetic material particles into a viscous, uncured polymer,

ii) spreading the mixture as a sheet on a flat substrate,

iii) applying a vertical magnetic field to align the rigid magnetic particles as a parallel, vertical chain-of-spheres,

iv) curing and solidifying the composite material by polymerization using heat, using time-dependent polymerization with a mixed in catalyst component, or using UV light illumination if the polymer matrix is a photo-sensitive curable material, so that parallel vertical chains of rigid spheres are permanently fixed in an elastically low modulus polymer matrix.

The rigid magnetic material is made of metal, alloy or ceramic material, and the polymer material is made of an elastomer, epoxy or other polymer materials. The polymer sheet material comprising the vertical chains of magnetic particles may be alternated with a sheet of low-modulus polymer material containing no particles. The curing of the polymer is carried out at a high temperature of at least 100°C, so that on curing and cooling to room temperature, a compressive stress is trapped in the composite material. An alternate method comprises pre-coating the rigid magnetic particles with a soft modulus polymer material.

The above methods will produce a pulse trapping device similar to that described in Fig. 1, but comprising polymer sheet material containing chains of rigid magnetic particles alternated with low-modulus polymer sheet material containing no particles.

Another embodiment comprises chains of rigid magnetic particles pre-coated with a soft modulus polymer material. In each of these embodiments the structure comprises rigid particles separated by soft particles, a soft sheet material or a soft coating. Alternatively, as illustrated in FIG. 2(C), the granular medium is provided with top and bottom face plates, which are mutually connected by a material which has much higher thermal contraction coefficient. On cooling from a high temperature or a curing temperature of an elastomer or epoxy, for example, the thermal contraction of elastomer or epoxy is much higher than stainless steel beads, and hence a compressive stress will be introduced on the chains along the vertical direction. Yet another way of introducing the pre-stress is to apply mechanical stress, for example by tightening screws or bolts/nuts on a top and bottom face plates, as illustrated in FIG. 2(C). The face plates should be relatively thin, yet mechanically stiff, for example, a steel plate or a titanium alloy plate. This also provides a method to tunably alter the amount of pre-stress on the ensembles of beads.

FIG. 3 schematically illustrates yet other alternative embodiments of pulse trapping devices with magnetically induced pre-stress according to the invention. FIG. 3(A) shows a portion of the cross-sections of the granular medium in which the pre-stress is induced by external electromagnetic field on magnetic beads (upper magnetic beads not shown) while FIG. 3(**B**) illustrate a case of compressive pre-stress introduced by a pair of magnets attracted and stuck to each other so as to pull the face plates together and apply a compressive stress on the chains of beads. This also provides a method of tunably altering the amount of pre-stress on the ensembles of beads by varying the strength of the magnetic field.

FIG. 4 (A) through (G) schematically illustrate an exemplary inventive method for making the shock-disintegrating granular structure. The support matrix **12** with patterned arrays of vertical holes can be prepared in a number of different ways as discussed earlier, according to the size and the materials used. The holes are prepared in such a way that the entrance (the upper part of the hole) is made slightly larger and in a funnel-like configuration for easy dropping of beads (balls) **10** into the holes. The laminar groups of beads **10** are then inserted layer by layer (A). The collection of grouped ensemble is important for maximizing the shock-disintegrating performance of the granular material as will later be discussed in reference to FIGs. 8-10.

The holes are occluded with a matching array of pins **32** attached to a planar base **30**, partially filling the cavities present in the support matrix **12**, so as to leave a certain desired height of the holes available for filling with the beads. The desired type of beads **10** (for example, starting with rigid beads of stainless steel) is placed on the top surface of the device, contained by some perimeter walls to avoid falling. The upper empty sections of the array of holes are then filled by the desired type of beads as illustrated in FIG. 4(**A**). The filling happens by self-assembling of the beads on shaking or vibrating the container. Once the first layer is filled (FIG 4**B**), any remaining beads on the surface are swept or blown away. The pin array **32** is then shifted down by a certain height corresponding to the desired thickness of the second beads-layer. The new beads **11** are then placed on the top. The cavity-filling step is then repeated to fill the empty space again (FIG. 4**C**). Such a filling step is then repeated (FIG. 4**D**) for the desired number of times, until the matrix gets completely filled (FIG. 4**E**) and capped with a top plate **34**. The top plate is desirably made relatively thin so as not to overly influence the pulse propagating characteristics. The typical desired thickness of the top (and the bottom) plate is in the range of 0.1 – 1 times the thickness of one bead. The material for the top plate can be the same type of material as one of the components of the bead assembly, i.e., either the soft or the rigid bead material. Alternatively, a thin layer or sheet of relatively soft, low-modulus material can be used as long as it has enough strength to retain the bead assembly and keep the beads from falling out. An example of such a layer is a piece of paper with desired thickness, an elastomer layer, a vinyl or other plastic sheets. In the case of shock or explosive impact, these layers can easily be squashed and minimally influence the pulse propagating behavior.

Once the bead assembly is completed, the pin array needs to be removed and the bottom side capped without allowing the beads to fall out. This can be accomplished by simply flipping upside-down the whole assembly of FIG. 4(**E**), as illustrated in FIG. 4(**F**), utilizing the gravity as the holding force for the assembled chain of beads. The capping plate is then added to complete the assembly of the three dimensional shock-disintegrating granular structure. (FIG. 4**G**).

An alternative way of holding the assembled chain of beads against gravity falling, according to the invention, is to use magnetic attractive force as illustrated in FIG 5. Some of the rigid beads (especially the bottom ball) have to be selected to be ferromagnetic in order to enable this process, for example, by using Ni, Co, Fe, or ferromagnetic 400 series stainless steel beads. Once the hole filling is completed (FIG. 5**A**) following the process of FIG. 4(**A-E**), a magnet **36** (permanent, or better yet, an electromagnet that can be turned on/off at will) is placed on top of the capping plate in order to hold the steel sections of the chain suspended (FIG. 5**B**) while a bottom plate **38** is attached to the assembly (FIG. 5**C**). The magnet is then removed and the composite granular medium is completed (FIG. 5**D**).

The inventive methods of FIG. 4 and FIG. 5 are described as a process flow chart as presented in FIG. 6.

The inventive granular medium can be fabricated by other techniques as well. In an example of an alternative, inventive method illustrated in FIG. 7, the vertical channels are filled with a desired mix of soft or rigid beads from the bottom side. A continuous (or semi-continuous) supply of the “rigid” beads **10** and “soft” beads **11** can be made from the bottom through a reservoir, or a vertical channel array, or a tube **50**. The upper assembly structure **12**, which will be the final shock protector, can be moved slightly sideways, back and forth, to hold the beads inserted into the upper structure. The two types of beads, soft **11** or rigid **10**, can be moved up through a piston-like structure at the bottom in a desired manner until a pre-planned sequence of soft and rigid bead assembly is completed. The beads can also be continuously supplied, for example, using a bead-supplying-tube actuated by a pneumatic mechanism **52**. Once the assembly of the balls is finished, a top plate and a bottom plate can be attached to hold the balls in place similarly as shown in FIG. 4 and FIG. 5.

EXAMPLE 1

The model system investigated is a single chain composed of integrated groups of shorter chains with drastically different elastic modulus. To create the "granular container" we used a total 32 beads, of which 22 beads were the high-modulus stainless steel beads (non-magnetic, 316 type) and 10 were the low-modulus PTFE (polytetrafluoroethylene) beads. The diameter of the beads was uniform, ~4.76 mm, and the bead arrangements in different configurations were investigated. The different arrangements were chosen to demonstrate the trapping of the pulse within the elastically softer regions and to optimize the configuration for the enhanced protection of the bottom wall from the incoming impulse shock, and FIGs. 8-10 present the results relative to the "optimal" configuration. For testing, three piezo-sensors were embedded inside particles in the system and a fourth sensor was embedded in the wall at the bottom of the chain. The calibrated sensors (RC $\sim 10^3$ μs), connected to a 4 channels Tektronix Oscilloscope (TKTDS 2014), allowed the direct visualization of the pulse propagating through each section of the chain (force versus time curves) and the time-of-flight calculations of the pulse speed through the chain. The particles were assembled in a vertical PTFE holder. Pulses were generated with a lighter, 0.47 g Al_2O_3 rod striker dropped from various heights for the single solitary wave type loading and also with a much heavier, 63 g Al_2O_3 rod for the shock-type loading. In addition, in order to tune the properties of this new "granular protector", a magnetically induced precompression (2.38 N) was applied.

Testing on a uniform chain composed of 32 stainless steel beads were first performed serving as a bench mark for the comparison. Thereafter, the double "granular container" (FIG. 8A) was tested. Here we alternated steel and PTFE portion of the chains with a periodicity 8-5-6-5-8, where the 5 particle portions are composed of PTFE beads only. The mass of a 316 stainless steel bead is 0.45 g, with a density of 8000 kg/m^3, Young's Modulus of 193 GPa and the Poisson's ratio is equal to 0.3. The mass of a PTFE bead is 0.123 g, the density 2200 Kg/m^3, the elastic modulus is 1.46 GPa, and the Poisson's ratio 0.46. Numerical analysis of the discrete chains was performed for all the set-ups described for the calculation of force-time curves as well as for the total energy trapped and released by the "granular containers". The simulations were run using the equation of motion for the grains obtained through the calculation of the contact forces between neighboring beads with Hertz contact. The presence of the gravitational precompression (caused by the vertical orientation of the tested chain) was kept into account in the numerical analysis although the effects of dissipation were not included in the calculations.

FIGs. 8(**B**) and 9(**A**) show the experimental results corresponding to the effectiveness of the trapping of a single solitary wave pulse in the double "granular container". It is evident that the first (uppermost) section of the PTFE works very efficiently trapping a larger amplitude of the pulse and transforming the 40 μs incoming pulse (from the steel section) into a much longer and delayed train of signals with an overall duration over a millisecond long. Numerical calculations FIG. 9(**B**) of the energy constrained in the "granular container" confirmed the higher efficiency as a protector: the double container traps the total (and potential) energy for a long time.

To further analyze the influence of the interfaces on the efficiency of the granular container we tested the double "granular container" under magnetically induced superimposed force. The static preload (FIG. 8(**C**) in experiments) resulted in an evident increase of the speed of the signal propagation and in the creation of an anomalous reflected wave on the first (uppermost curve) steel sensor followed by a series of multiple reflected pulses (called as acoustic diode behavior). It is evident that the introduction of the preload significantly reduced the force impulse acting on the wall, facilitating the splitting of the signal into a train of low-amplitude waves. The physical explanation for such an efficient confinement of the pulse in the softer region of the chain is connected to the formation of gaps at the interfaces causing some complex "rattling" among the interfacial particles combined with the reflection of the pulse from the interfaces of the softer region. This allows the two "granular containers" to keep the energy trapped longer, therefore enhancing the protection of the wall. More specifically, when the signal propagates through the first interface, a "fracture wave" is formed and a series of gaps are opened between the last steel particles and the interface. The presence of these opening and closing gaps is enhanced by the static precompression and is responsible for the introduction of a new time-scale in the system as well as to the formation of an unusual reflected wave at the interface under precompression (top curve of Fig. 8C).

As a result, the gaps delay the wave reflection and propagation and enhance backward reflections from the heavy/light interfaces. In this case the total energy trapped in the softer sections remains basically constant with time. Furthermore the superimposed force transforms the pulse arriving at the wall in a series of definitely separated impulses, reducing the total momentum reaching the bottom wall. This behavior is very useful as a mean to protect an object from incoming impacts by providing longer distances of pulse traveling within the protector region, thus causing the impact to lose its energy due to dissipation.

This double configuration was also shock loaded as shown in Fig. 10. Here the striker used was an Al_2O_3 rod (63 g) dropped on the first steel bead. In experiments (FIG. 10**A**) the signal reaching the wall was transformed from an oscillatory, fast-ramping shock loading into a long, slowly increasing series of pulses, which is likely to be much less damaging to the protected object (the end wall in this experiments). The double "granular container" provided a very efficient transformation of the signal reaching wall in a much longer ramping time and lower amplitude, suitable for best shock-protection. Numerical calculations (FIG. 10**B**), found in qualitative agreement with the experiments, demonstrated that under shock-type loading the softer sections of the chain do not appear to trap energy only acting as pulse transformers. Calculations were also performed for a chain composed of one-by-one alternating stainless steel and PTFE beads, to see if the increasing the number of interfaces throughout the chain further improves the shock protection. In this case the chain responded as a homogenized "two-particle system" reducing drastically the efficiency of the protector.

In conclusion, we demonstrated experimentally and numerically the efficiency of soliton-like and shock-like pulse trapping and energy leaking in a high-/low-modulus composite structured "granular container" and proved that the efficiency of the protector depends on the particle arrangements with the stronger effect obtained in a grouped configuration. Under shock-type loading a drastic modification of the signal ramp time at the wall was obtained more pronouncedly in the "double container" configuration. The application of a magnetically induced precompression divided the signal reaching the wall in a series of subdivided pulses reducing the total force impulse. If properly configured, these grouped composite media can be building blocks for powerful energy absorbers against impacts, and can be useful as efficient protectors for technological and security applications.

Yet another alternative method of creating impact-disintegrating structures include a layered granular medium as illustrated in Fig. 11(A). The structure utilizes a pre-made (e.g., machined or stamped) layer of high-modulus material **60** and that of a low-modulus material **62** alternately stacked, with protruding features of each material easily aligned against each other for contact interactions and wave behavior control. A variation of the Fig. 11(A) is the structure illustrated in Fig. 11(B) in which the high modulus material is in the form of a sphere (**65**) while the low modulus material is in the form of grooved or stamped configuration (**66**) to hold the high modulus balls in place. These layers are repeatedly stacked for contact interactions when an impact wave comes onto the top of the structure. The remainder of the structure, **64** and **68**, can be either a support plate or can be another material with a different modulus. Uniform contacts between the high modulus material and the low modulus material are guaranteed by the presence of the pre-grooved structure.

FIG. 12 (**A-D**) schematically illustrate applications for the composite granular structure. It includes implementations as a coating for bullet-proof vests, helmets and other protective gear, for construction or military hazards (FIG. 12**A**), a vehicle protection layer against explosives (FIG. 12**B**), sound-proof coatings or layers for buildings, offices or home sound-proof coatings (FIG. 12**C**), freeway noise-reducer-walls, and other examples, such as a device that allows a soft-landing of airplanes, helicopters or spacecrafts, such as lunar or Mars vehicles, or for athletes or military commandos jumping or vertically descending. Another application is for a highly protective shipping container for delicate machinery (FIG. 12**D**). The container in the Fig. 12(**D**) structure can also be a protective outer case for electronic equipment, such as cell phones, portable digital cameras or music players, so that accidental dropping of such equipment does not create severe permanent damage.

Inventive 3-D tunable phononic crystals, as focus adjustable acoustic lenses, comprising chains of the shock-disintigrating structure 70, as desribed hereinabove, with an ability to alter the focus or intensity of acoustic beams, are also useful for devices with a tunable acoustic source, as illustrated in Fig. 13. Tunable acoustic devices are useful for nondestructive testing of defects in bridges, aircraft materials or vehicles, as well as for certain biomedical applications. For example, a delicate brain surgery based on an ultrasonic beam to kill the tumor cells, requires a precise control of the position of the focused acoustic beam so that the desired operation is accomplished with minimal damage to the nearby brain cells. Such an application, of a tunable phononic crystal, is schematically illustrated in Fig. 14. Acoustic energy or mechanical vibration may also be utilized for therapeutic applications to stimulate or disable certain diseased cell functions, such as in various organs or in the brain when the cells respond to the acoustic energy. The inventive tunable phononic crystals may also be utilized for other applications such as kidney stone treatment, with a well-focused acoustic beam, or accelerated growth and healing of damaged or broken bones, according to the invention.

It is to be understood that the above-described embodiments are illustrative of only a few of the many possible specific embodiments, which can represent applications of the invention. Numerous and various other arrangements can be made without departing from the spirit and scope of the invention.

The Invention Described Herein Comprises:

1. A vertically aligned, three-dimensionally configured, strongly nonlinear composite granular structure which enables a forced energy confinement and disintegration of impulses propagating in a strongly nonlinear laminar granular medium, which consists of mixed chains-of-spheres of high elastic modulus

(rigid) beads and low modulus (soft) beads. Various variations of structural parameters and material parameters are available in the structure of #1.

2. Structure #1 wherein the pulse propagation and disintegration characteristics are tuned by mechanical pre-stress.
3. Structure #1 wherein the pulse propagation and disintegration characteristics are tunable by magnetically induced pre-stress.
4. Fabrication methods for assembling a vertically aligned, three-dimensionally configured, strongly nonlinear composite granular structure of structure #1-3, which consists of a mixed chains-of-spheres of high elastic modulus beads and low modulus beads, and which is capable of a forced energy confinement and disintegration of impulses propagating in a strongly nonlinear laminar granular medium.
5. A vertically aligned, three-dimensionally configured, strongly nonlinear composite granular structure which enables a forced energy confinement and disintegration of impulses propagating in a strongly nonlinear laminar granular medium, which consists of two types of material of high elastic modulus material and low modulus material in an alternately stacked layer arrangement, with at least one type of material in a pre-made patterned or grooved configuration.
6. Article comprising bullet-proof vests, helmets and other protection gear for construction or military hazards, with the vests and helmets containing the pulse-disintegrating structure of #1-5.
7. Article comprising vehicles protection layer against explosives, with the layer containing the pulse-disintegrating structure of #1-5.

8. Article comprising sound-proof coatings or layers for buildings, offices, homes, freeway noise-reducer-walls, with such coatings or layers containing the pulse-disintegrating structure of #1-5.
9. Article comprising a device containing the pulse-disintegrating structure of #1-5, which allows a soft-landing of airplanes, helicopters or spacecrafts such as lunar or Mars vehicles, or athletes or military commandos jumping or vertically descending, or a highly protective shipping container for delicate equipment.
10. Article comprising a portable device containing the pulse-disintegrating structure of #1-5, which protects electronic equipment such as cell phones, portable digital cameras or music players, so that accidental dropping of such equipment does not cause severe permanent damage.
11. Article comprising tunable phononic crystals, utilized for biomedical applications including brain surgery, therapeutic treatment of diseased cells or organs, destruction of kidney stones and calcium deposits in a human or animal body.
12. Various methods of assembling three-dimensional phononic crystal materials, as illustrated in FIGs. 1-7.
13. Various methods of using phononic crystals for applications described in FIGs. 13-14.

Industrial Applicability

The devices described herein may be utilized for bullet-proof vests, helmets and other protection gear for construction or military hazards, vehicle protection layers for protection against explosives, sound-proof coatings or layers for buildings, offices, homes, freeway noise-reducer-walls, devices which allow a soft-landing of airplanes, helicopters or spacecrafts or athletes or military commandos jumping or vertically descending, or highly protective shipping containers for delicate equipment. Portable device can protect electronic equipment such as cell phones, portable digital cameras or music players, so that accidental dropping of such equipment does not cause severe permanent damage. In addition, tunable phononic crystals may be utilized for biomedical applications including brain surgery, therapeutic treatment of diseased cells or organs, destruction of kidney stones and calcium deposits in a human or animal body.

Having thus described the invention, the scope of the invention shall be defined by the following claims:

We Claim:

Claim 1. A pulse trapping device comprising an array of composite chains of alternating ensembles of soft beads and rigid beads in a supporting matrix.

Claim 2. The pulse trapping device of Claim 1 in which the difference in the elastic moduli of the soft beads and rigid beads is at least 10.

Claim 3. The pulse trapping device of Claim 1 in which the difference in the elastic moduli of the soft beads and rigid beads is at least 100.

Claim 4. The pulse trapping device of Claim 1 in which the beads are arrayed in vertical chains.

Claim 5. The pulse trapping device of Claim 1 in which the rigid beads are made of steel and the soft beads are made of polytetrafluoroethylene.

Claim 6. The pulse trapping device of Claim 1 in which the soft beads have a Young's elastic modulus in the range of 0.1 to 5000 MPa.

Claim 7. The pulse trapping device of Claim 1 in which the soft beads have a Young's elastic modulus in the range of 100 to 1000 MPa.

Claim 8. The pulse trapping device of Claim 1 in which the rigid beads have a Young's elastic modulus in the range of 1 to 400 GPa.

Claim 9. The pulse trapping device of Claim 1 in which the chains of beads comprise alternating ensembles of from 1 to 24 soft beads in a row and from 1 to 24 rigid beads in a row.

Claim 10. The pulse trapping device of Claim 1 in which the chains of beads comprise alternating ensembles of at least 2 soft beads in a row and at least 2 rigid beads in a row.

Claim 11. The pulse trapping device of Claim 1 in which the diameter of the beads is from 0.001 mm to 1000 mm.

Claim 12. The pulse trapping device of Claim 1 in which the matrix is made from a metal, alloy, silicon, wood, polymer material, or a composite comprising at least two of these component materials.

Claim 13. The pulse trapping device of Claim 1 further comprising a mechanical structure to pre-stress the ensembles of beads.

Claim 14. The pulse trapping device of Claim 13 wherein the mechanical pre-stress structure further comprises means to tunably alter the amount of pre-stress.

Claim 15. The pulse trapping device of Claim 1 in which a portion of the beads are magnetic and further comprising an electromagnetic device to pre-stress the ensembles of beads.

Claim 16. The pulse trapping device of Claim 15 wherein the electromagnetic device further comprises means to tunably alter the amount of pre-stress.

Claim 17. The pulse trapping device of Claim 1 in which the ensemble of beads are arranged in an off-axis alignment.

Claim 18. The pulse trapping device of Claim 1 further comprising top and bottom face plates attached to the matrix.

Claim 19. The pulse trapping device of Claim 18 further comprising means to tighten the top and bottom face plates together to apply pre-stress to the array of ensembles of beads.

Claim 20. A shock absorption device comprising a vertically aligned, three-dimensionally configured, composite granular structure having a high elastic modulus material and low modulus material in an alternately stacked layer arrangement.

Claim 21. A method for manufacturing a pulse trapping device comprising a support matrix having a patterned array of vertical holes, widening the upper part of each hole in a funnel-like shape, occluding each hole with an array of pins attached to a planar base, inserting in each said hole a first layer of either soft beads or rigid beads, shifting the pin array down by a designated height corresponding to the desired thickness of the second bead layer and inserting in each said hole a second layer of soft beads if the first bead layer was rigid or rigid beads if the first bead layer was soft, repeating this procedure until the holes are filled to the top with beads, capping the top of the matrix with a top plate and capping the bottom of the matrix with a bottom plate.

Claim 22. The method of Claim 21 comprising turning the matrix upside-down after the top plate is attached in order to attach the bottom plate.

Claim 23. The method of Claim 21 in which some or all of the rigid beads are magnetic and the beads are held in place by an electromagnet in order to attach the bottom plate.

Claim 24. A method for manufacturing a pulse trapping device comprising a support matrix having a patterned array of vertical holes, inserting in each said hole from the bottom, a first layer of either soft beads or rigid beads, using a piston assembly at the bottom of the matrix, shifting the matrix sideways to block the bottom of the holes, loading onto said pistons and inserting in each said hole a second layer of soft beads if the first bead layer was rigid or rigid beads if the first bead layer was soft, repeating this procedure until a pre-planned sequence of soft and rigid beads is completed.

Claim 25. The method of Claim 24 further comprising attaching a top and bottom plate after the loading of the beads has been completed.

Claim 26. A method for manufacturing a three-dimensional pulse trapping device comprising:

i) mixing rigid magnetic particles into a viscous, uncured polymer,

ii) spreading the mixture as a sheet on a flat substrate,

iii) applying a vertical magnetic field to align the rigid magnetic particles as a parallel, vertical chain-of-spheres,

iv) curing and solidifying the composite material by polymerization using heat, using time-dependent polymerization with a mixed in catalyst component, or using UV light illumination if the polymer matrix is a photo-sensitive curable material, so that parallel vertical chains of rigid spheres are permanently fixed in an elastically low modulus polymer matrix.

Claim 27. The method of manufacturing a three-dimensional pulse trapping device of Claim 26 wherein the rigid magnetic material is made of metal, alloy or ceramic material, and the polymer material is made of an elastomer or epoxy.

Claim 28. The method of manufacturing a three-dimensional pulse trapping device of Claim 26 wherein the polymer sheet material comprising the vertical chains of magnetic particles is alternated with a sheet of low-modulus polymer material containing no particles.

Claim 29. The method of manufacturing a three-dimensional pulse trapping device of Claim 26 wherein the curing of the polymer is carried out at a temperature of at least 100°C, so that on curing and cooling to room temperature, a compressive stress is trapped in the composite material.

Claim 30. The method of manufacturing a three-dimensional pulse trapping device of Claim 26 wherein the rigid magnetic particles are pre-coated with a soft modulus polymer material.

Claim 31. A pulse trapping device comprising polymer sheet material containing chains of rigid magnetic particles alternated with low-modulus polymer sheet material containing no particles.

Claim 32. A pulse trapping device comprising chains of rigid magnetic particles pre-coated with a soft modulus polymer material.

Claim 33. A pulse trapping device comprising a bullet-proof vest, helmet or other protection gear comprising the pulse trapping structures of Claims 1-5.

Claim 34. A pulse trapping device comprising a vehicle protection layer against explosives, comprising the pulse-disintegrating structures of Claims 1-5.

Claim 35. A pulse trapping device comprising sound-proof coating layers for buildings, offices, homes, freeway noise-reducer-walls, comprising the pulse-disintegrating structures of Claims 1-5.

Claim 36. A pulse trapping device comprising adapted to allow the soft-landing of airplanes, helicopters or spacecraft, or athletes or military commandos jumping or vertically descending, comprising the pulse-disintegrating structures of Claims 1-5.

Claim 37. A pulse trapping device comprising a highly protective shipping container for delicate equipment, comprising the pulse-disintegrating structures of Claims 1-5.

Claim 38. A pulse trapping device comprising a structure to protect sensitive equipment, cell phones, digital cameras or music players, comprising the pulse-disintegrating structures of Claims 1-5.

Claim 39. A pulse trapping device comprising a tunable phononic crystal, utilized for biomedical applications including brain surgery, therapeutic treatment of diseased cells or organs, destruction of kidney stones and calcium deposits in a human or animal body comprising the pulse-disintegrating structures of Claims 1-5.

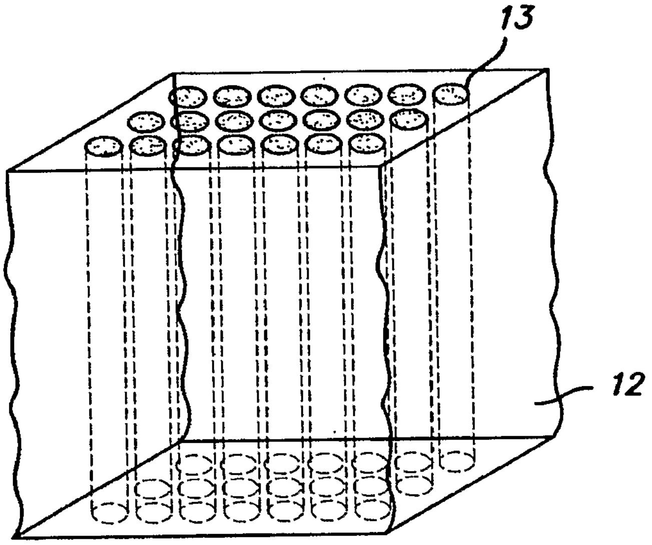


FIG. 1A

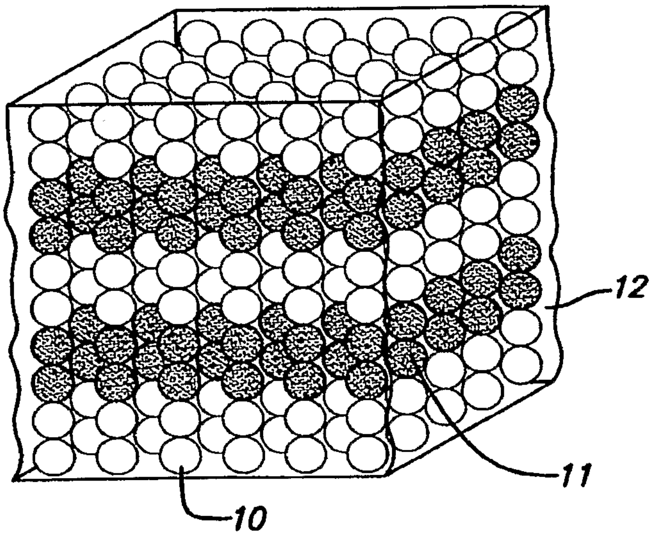


FIG. 1B

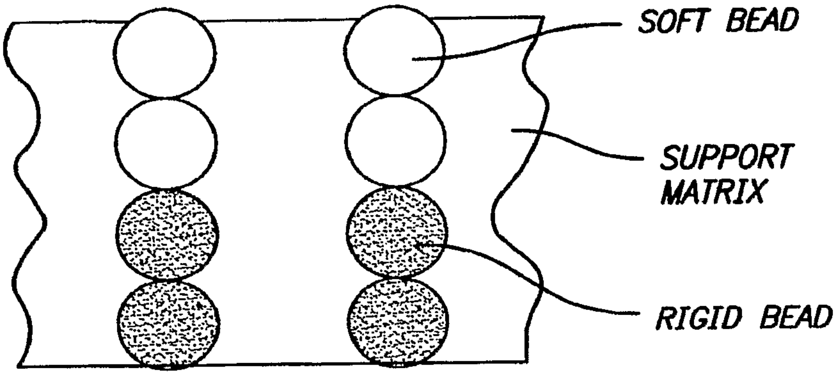


FIG. 2A

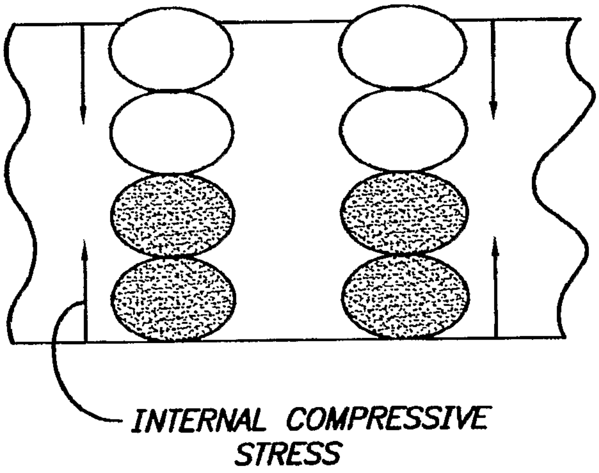


FIG. 2B

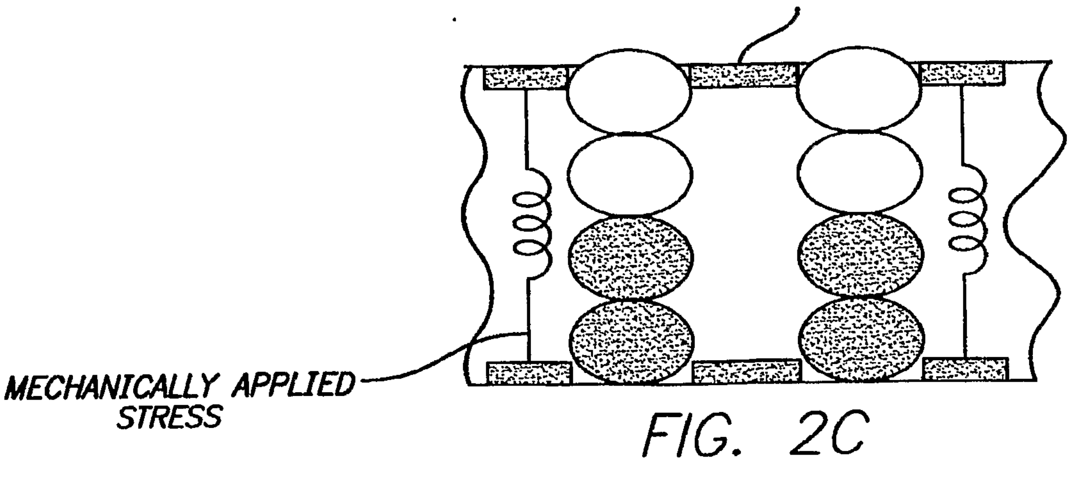


FIG. 2C

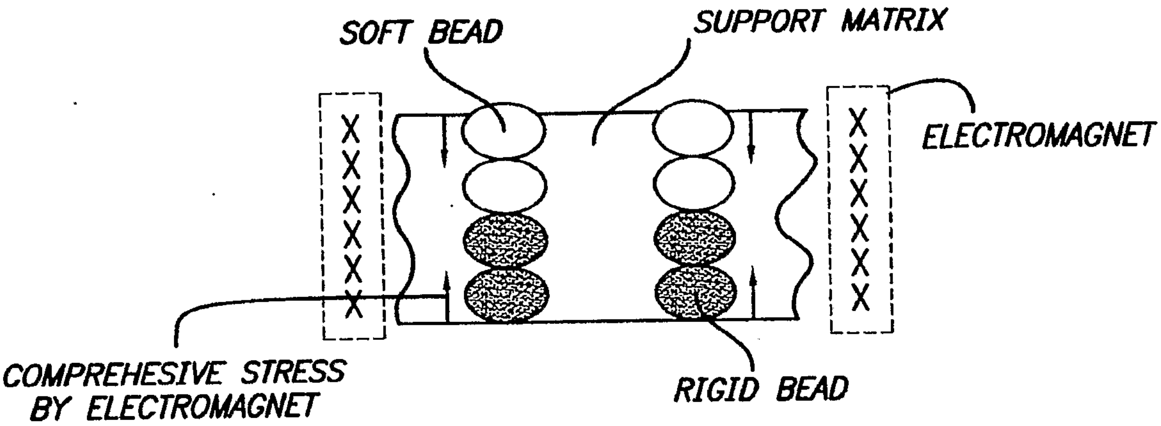

SOFT BEAD
SUPPORT MATRIX
ELECTROMAGNET
COMPREHESIVE STRESS
BY ELECTROMAGNET
RIGID BEAD

FIG. 3A

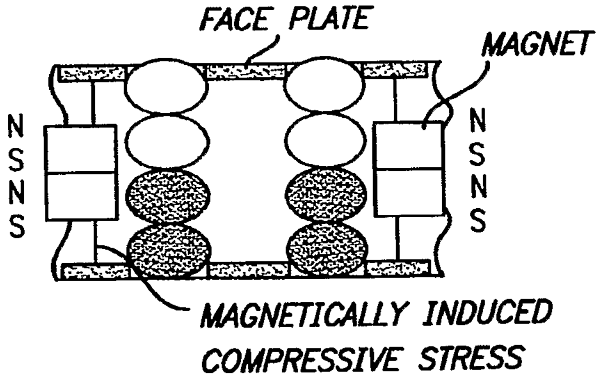

FACE PLATE
MAGNET
N
S
N
S
N
S
N
S
MAGNETICALLY INDUCED
COMPRESSIVE STRESS

FIG. 3B

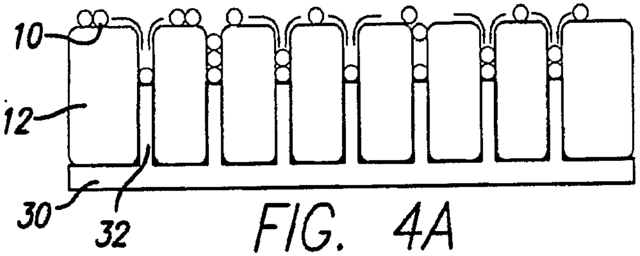


FIG. 4A

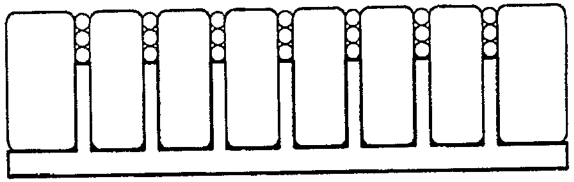


FIG. 4B

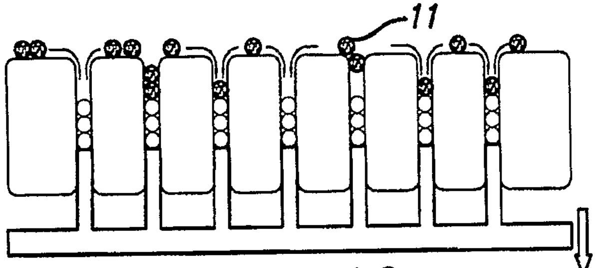


FIG. 4C

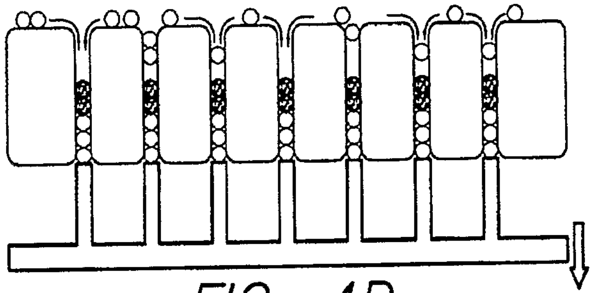


FIG. 4D

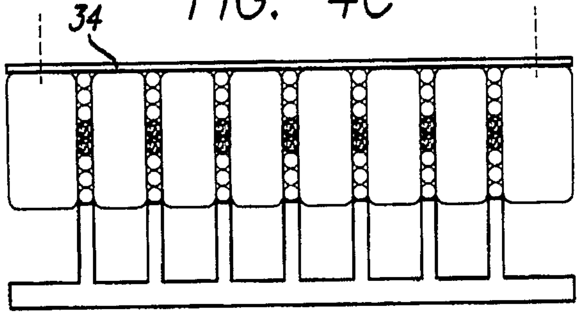


FIG. 4E

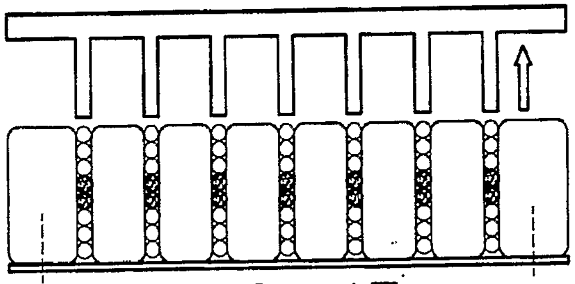


FIG. 4F

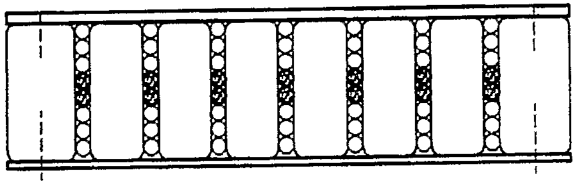


FIG. 4G

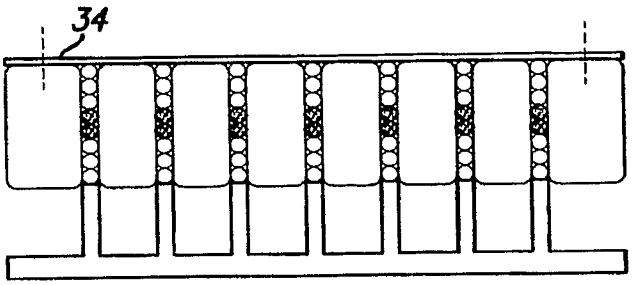


FIG. 5A

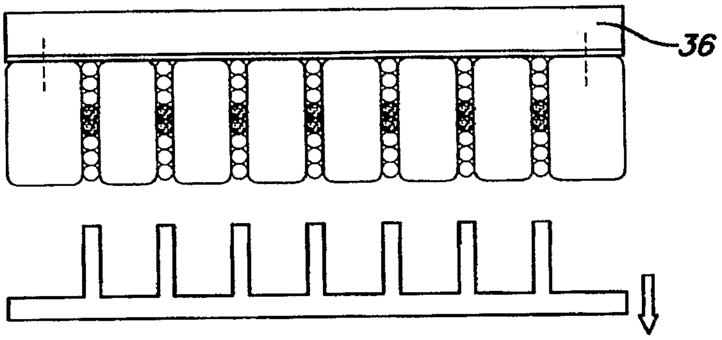


FIG. 5B

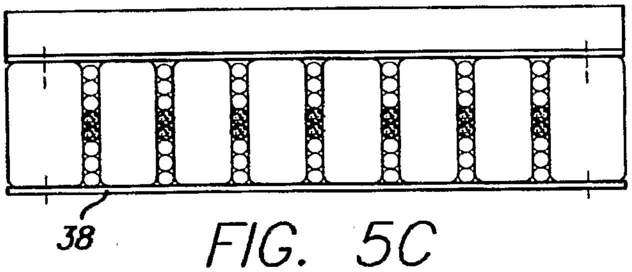


FIG. 5C

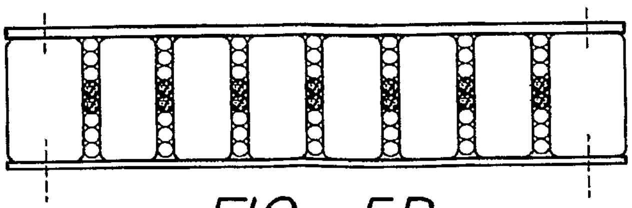


FIG. 5D

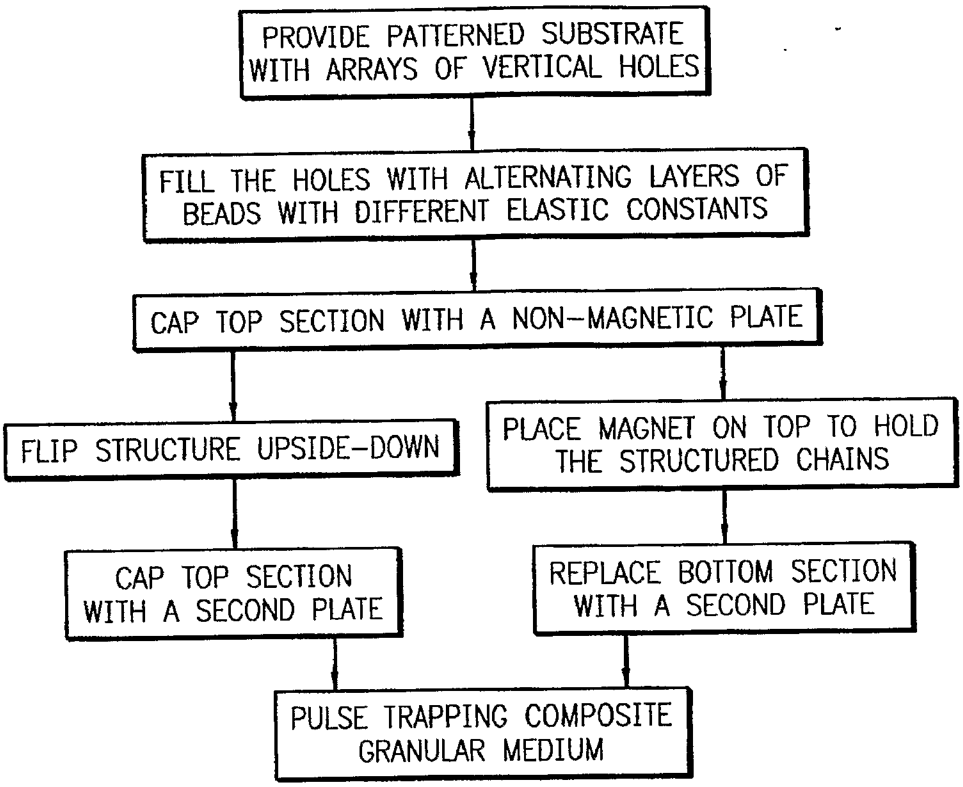

PROVIDE PATTERNED SUBSTRATE WITH ARRAYS OF VERTICAL HOLES
FILL THE HOLES WITH ALTERNATING LAYERS OF BEADS WITH DIFFERENT ELASTIC CONSTANTS
CAP TOP SECTION WITH A NON-MAGNETIC PLATE
FLIP STRUCTURE UPSIDE-DOWN
PLACE MAGNET ON TOP TO HOLD THE STRUCTURED CHAINS
CAP TOP SECTION WITH A SECOND PLATE
REPLACE BOTTOM SECTION WITH A SECOND PLATE
PULSE TRAPPING COMPOSITE GRANULAR MEDIUM

FIG. 6

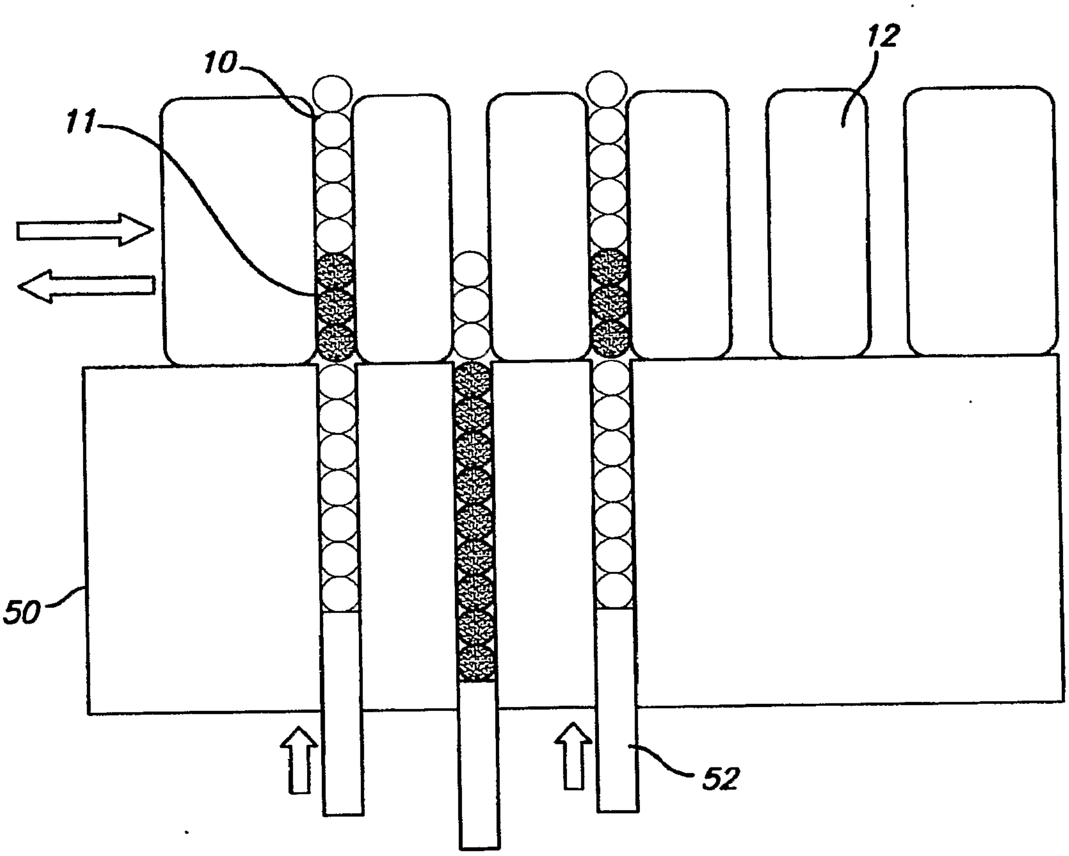


FIG. 7

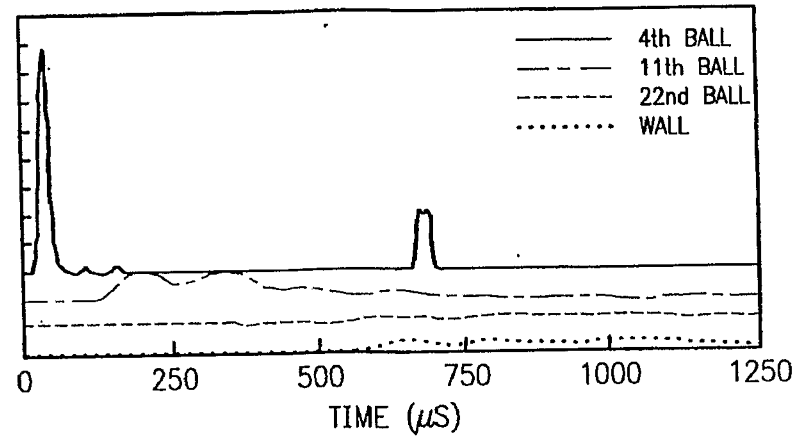


FIG. 8B

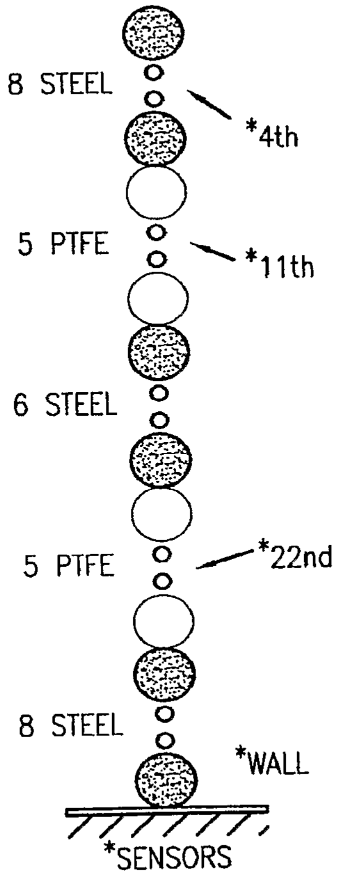


FIG. 8A

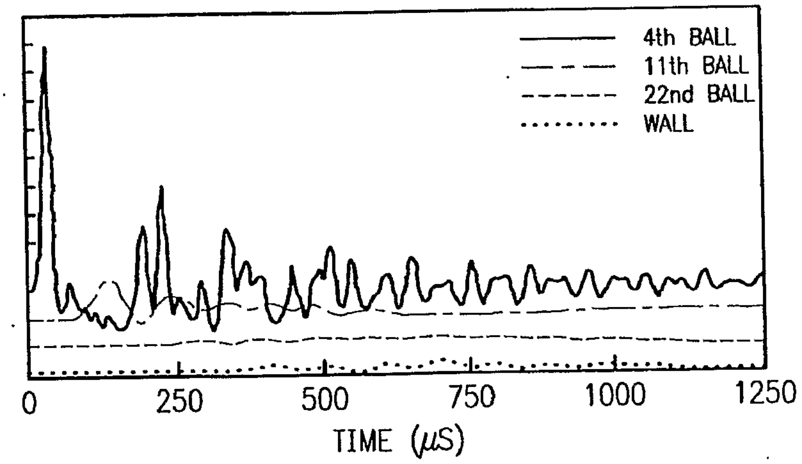


FIG. 8C

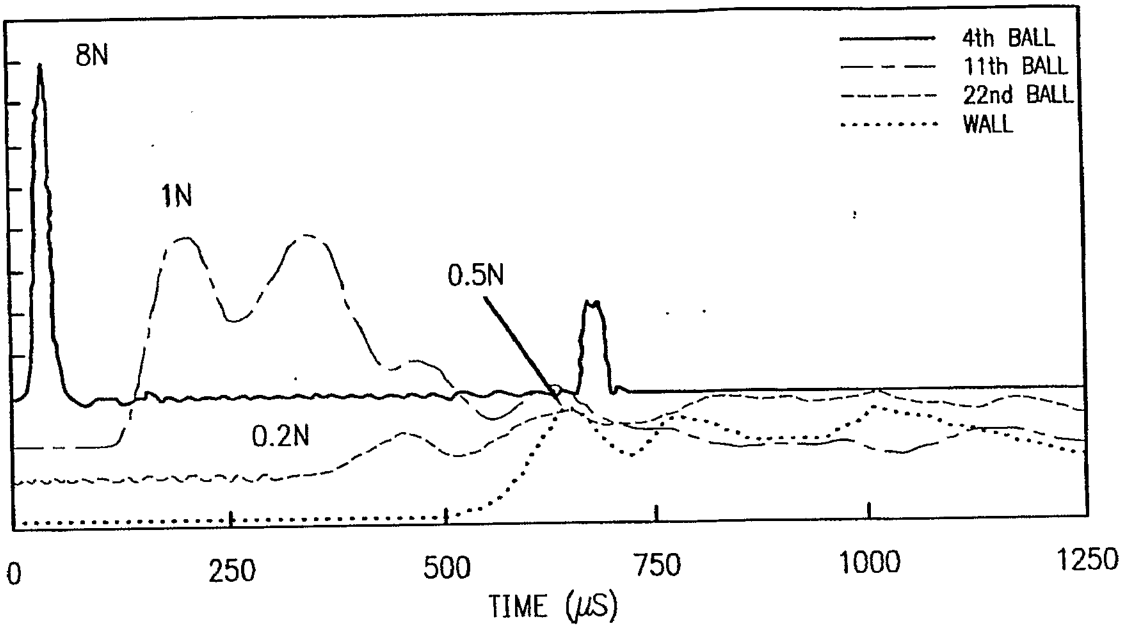

8N
1N
0.5N
0.2N
4th BALL
11th BALL
22nd BALL
WALL
0
250
500
750
1000
1250
TIME (μS)

FIG. 9A

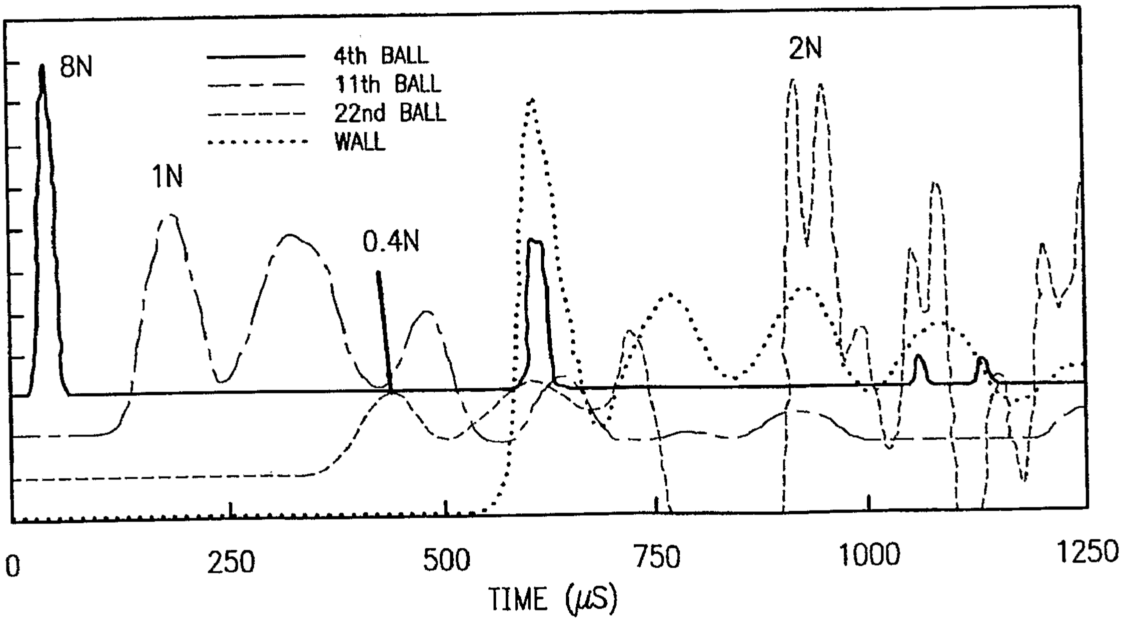

8N
1N
0.4N
2N
4th BALL
11th BALL
22nd BALL
WALL
0
250
500
750
1000
1250
TIME (μS)

FIG. 9B

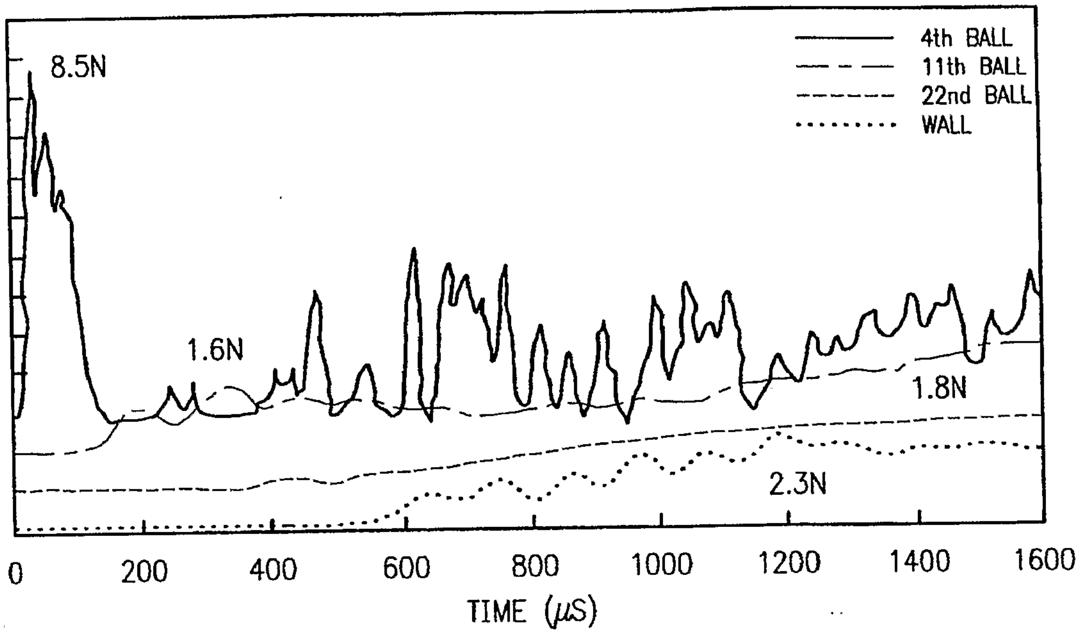


FIG. 10A

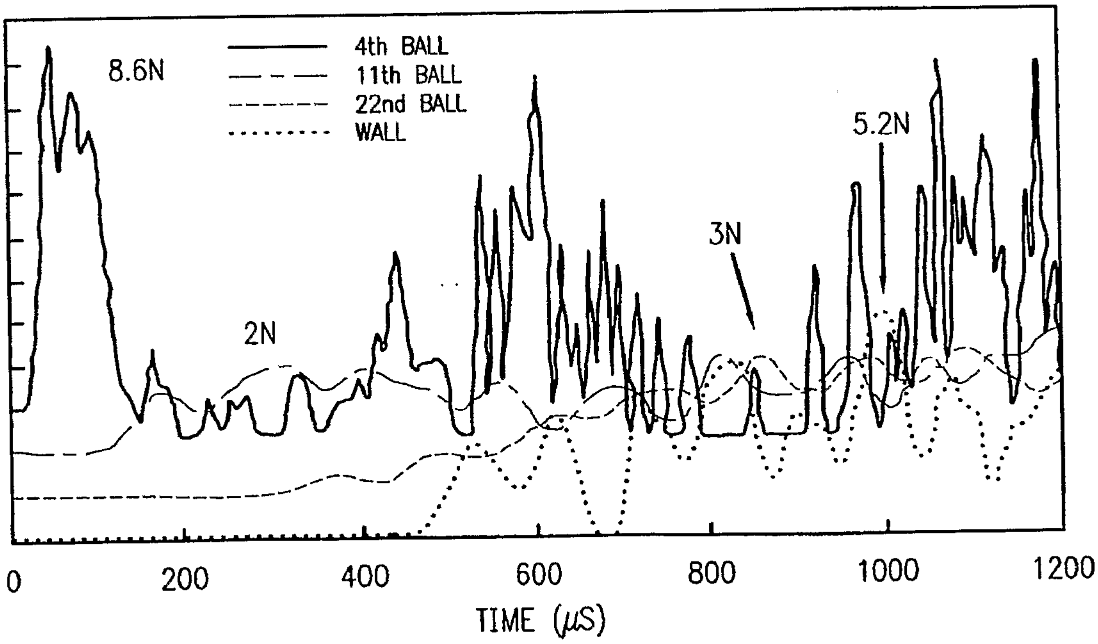


FIG. 10B

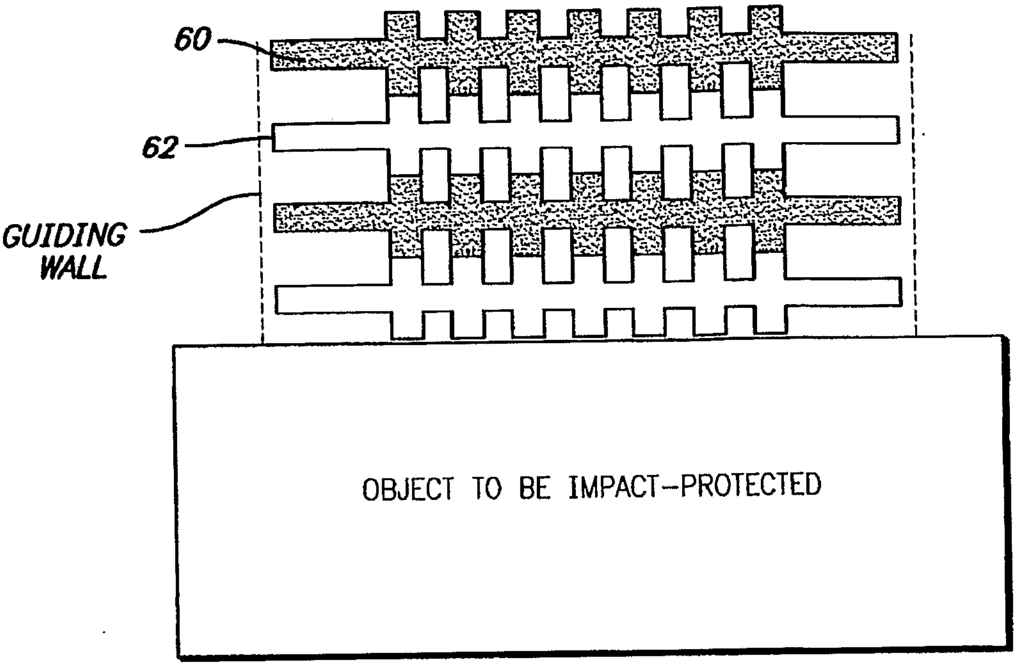


FIG. 11A

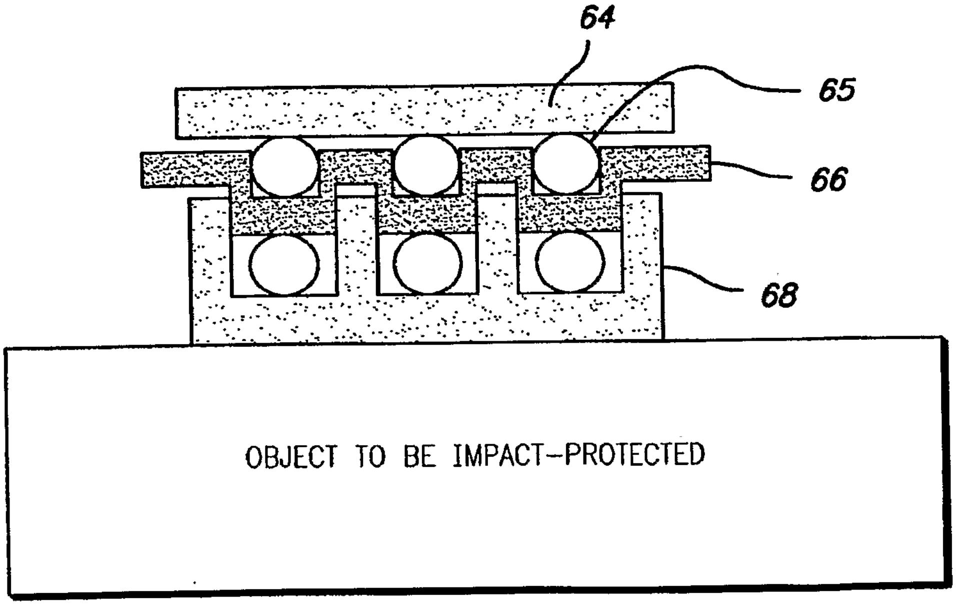


FIG. 11B

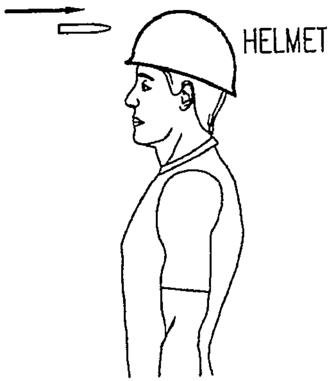


FIG. 12A

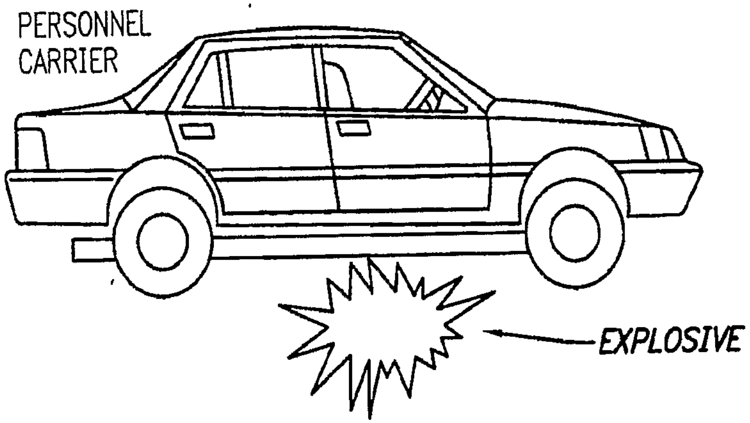


FIG. 12B

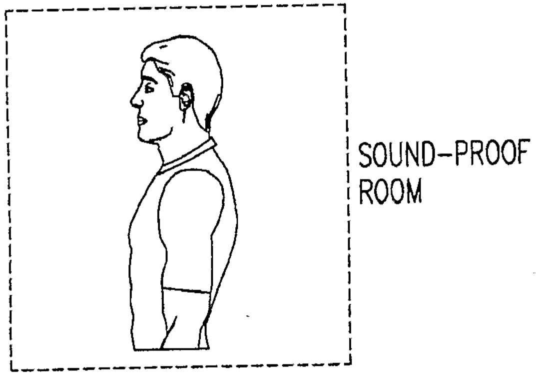


FIG. 12C

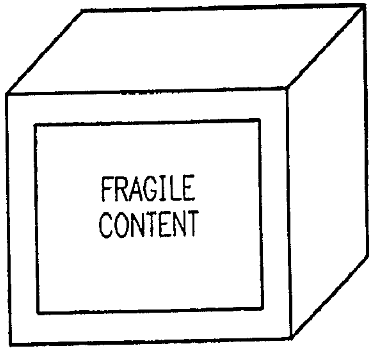
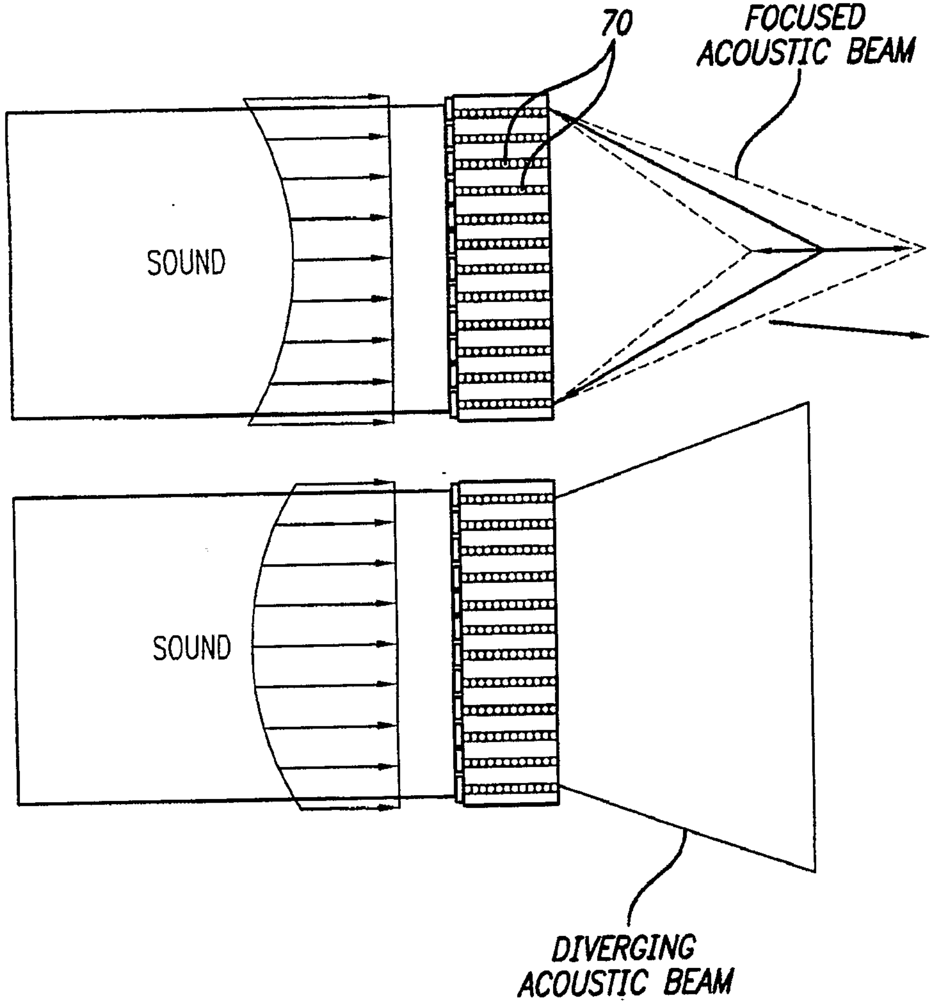


FIG. 12D



TUNEABLE PRE-COMPRESSION CAN INDUCE TUNABLE FOCUSING OF ACOUSTIC BEAMS, THUS ALLOWING AN ACCURATE BEAM POSITIONING---CAN BE USEFUL, FOR EXAMPLE, FOR DELICATE MICRO-SURGERY ON BRAIN TUMORS, KIDNEY STONES, THERAPEUTIC APPLICATION OF ACOUSTIC BEAMS, ETC.

FIG. 13

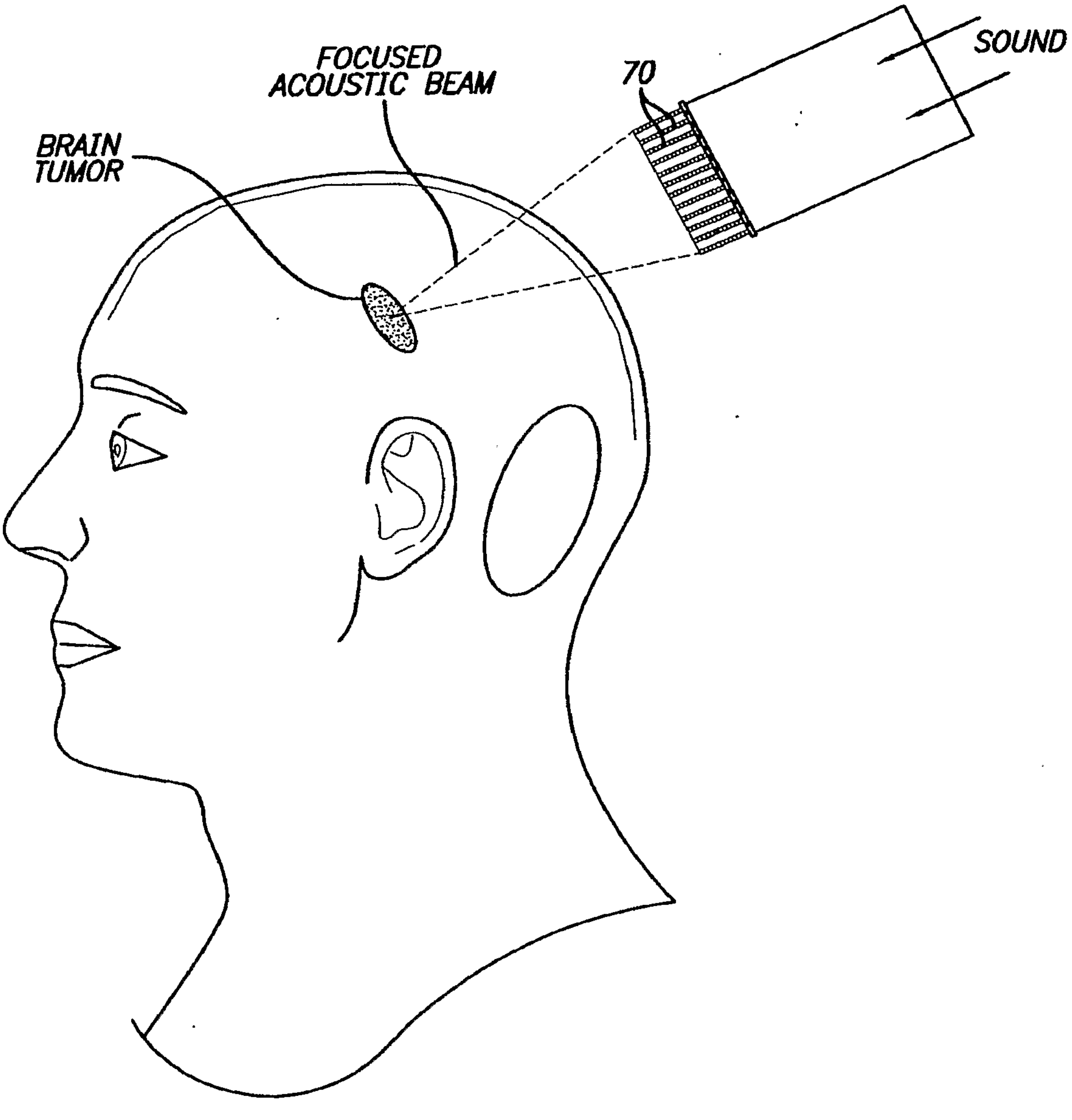


FIG. 14