Oct. 3, 1967 A. G. BODINE 3,344,874

LOW-IMPEDANCE ISOLATOR FOR VIBRATORY PILE DRIVER MACHINES

Filed May 28, 1965

FIG. 4

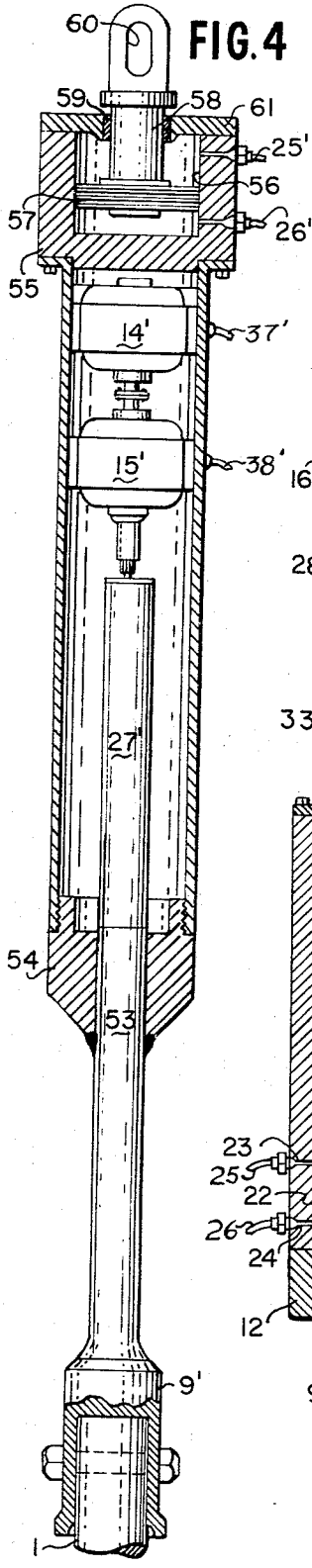


FIG. 2

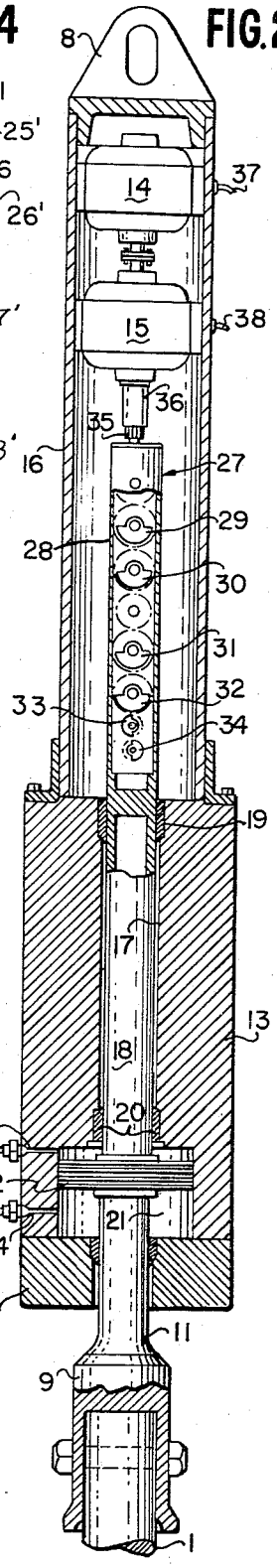
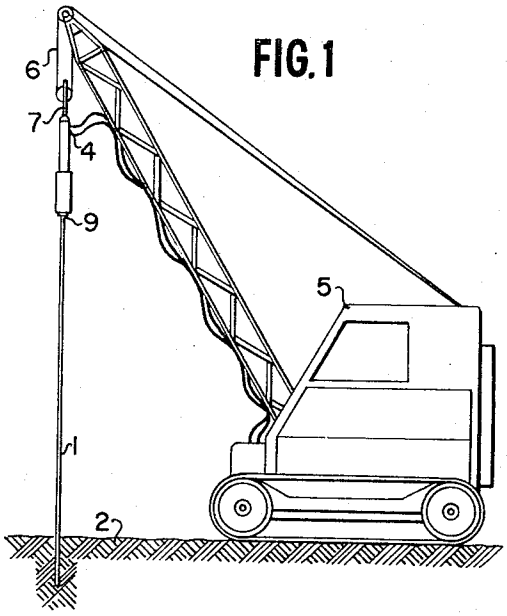


FIG. 1



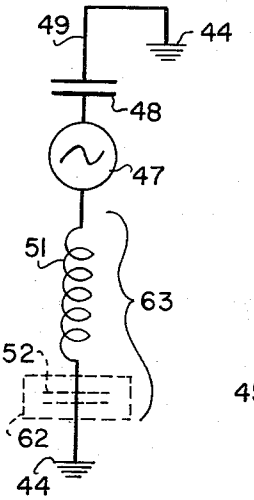


FIG. 5

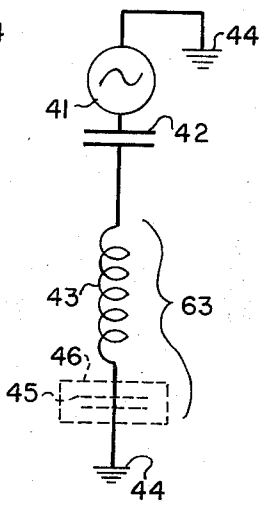


FIG. 3

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LOW-IMPEDANCE ISOLATOR FOR VIBRATORY PILE DRIVER MACHINES

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ABSTRACT OF THE DISCLOSURE

The low-impedance isolator decouples the vibration of the pile and drive assembly from the support assembly by means of a substantial body of compressed gas suitably confined to provide a low acoustic impedance.

This application is a continuation-in-part of application Ser. No. 183,608, now Patent No. 3,193,027, which is a division of application Ser. No. 710,956, now Patent No. 3,054,463.

This invention relates to pile driving apparatus and more particularly to novel isolator means for preventing unwanted transmission of the vibratory action of a pile driver into the associated structure supporting the pile driver.

There is disclosed in my Patent No. 2,975,846 entitled Acoustic Method and Apparatus for Driving Piles, sonic pile driving apparatus suitable for generating an elastic wave which is propagated into a pile to establish a standing wave vibration therein causing it to be driven downwardly into the earth. Other types of pile driving devices employing vibratory motion, but which do not necessarily depend upon resonance phenomena, as employed in the above-mentioned sonic pile driving apparatus, have also been proposed heretofore. Hereinafter these non-resonant types of pile driving devices will be referred to as bodily-vibration devices. In devices such as these the upper end of the pile and/or the vibrating driver unit is usually supported from some type of crane or derrick structure via a cable system. This cable system may comprise a complex system of guide and supporting lines, or it may be a simple cable and hook hanging from the boom of a crane. Usually this support means is needed in order to control the penetration rate, or equally important, to guide the direction of the pile as it enters the earth.

In some instances it is desired to extract the pile member from the ground in which case the support means is used to provide a pulling tension in such operation while the pile is being vibrated. In this case, wherein the pile is to be extracted, the support or pulling means provides the very essential function of the pulling tension and because of the large pulling force required, the pulling means must be intimately connected to the pile member. As can be seen from the foregoing, whether the pile is being driven into the earth or extracted therefrom, there must necessarily be a substantial physical connection between the supporting means and the pile and its driver unit.

A major problem arises in that the vibration of the pile, and the vibration of the driver unit, tends to be transmitted into the supporting structure. These transmitted vibrations generally have substantial power and if coupled into the supporting structure would result in violent vibration thereof and possible damage or destruction. For example, in the instance where cables are used to support the pile and its driver unit, the cables may undergo violent vibrations which would then transmit substantial and possibly destructive forces into the associated main structure to which the cables are attached. A crane to which the cables are attached, for example, may thereby be driven into violent vibration beyond its structural limits, resulting in damage as well as transmission of extreme vibration to

the wheels or tracks of the crane and to the ground. These ground transmitted vibrations are very troublesome throughout the area in which the pile driving operation is taking place.

It has been found that these vibrations are affected and modified by the very driving operation itself. That is, the characteristics of the vibrations are uniquely affected as a result of the piles being pounded non-linearly against the granular soil, which is highly absorptive of acoustic energy, while the vibrator is operating. This applies to the more simple bodily-vibration pile drivers, as well as to the sonic or resonant-vibration types of pile drivers. The result is that particular forms of extreme vibrations and shocks, having a unique characteristic of violence, are transmitted into the support structure in response to such vibratory pile driving operations. This vibration problem with its broad spectrum of frequency content is very troublesome.

The present invention is based upon the discovery that novel low-impedance vibration isolators, constructed in accordance with the invention, can be located between the pile member and the above-mentioned support structure, or between the driver unit and the support structure, with the result that there is a substantial amelioration of the problem of the transmission of unwanted vibration. In this connection, it should be noted that even though the pile driving operation might be accomplished by means of a non-sonic device, in other words even though it might be a simple bodily-vibration device, nevertheless an isolator in accordance with the present invention is especially effective in accomplishing the desired vibration isolation. Therefore, it should be understood that the acoustic properties of the low-impedance isolator devices of the invention do not require that they be necessarily limited to use in connection with sonic types of pile drivers, but may be used in connection with other types of mechanical oscillators.

In one form of the invention the low-impedance isolator decouples the vibration of the pile and driver assembly from the support assembly by means of a substantial body of compressed gas suitably confined to provide the required low acoustic impedance, or capacitive response device. Such a compressed body of required gas provides an extremely large difference of acoustic impedance between the two assemblies because the acoustic impedance of such a gas body is very low, relative to the impedance of any vibratory pile system. This is desired because of the high-frequency content of the shock spectrum generated and which is desired to be decoupled. As used in this specification, the impedance concept relates to the ratio of vibratory force to vibratory motion. In other words, a vibratory pile driver is a fairly massive combination having large cyclic force or inertia, in relation to the amplitude of its cyclic motion. The important concept is that such a large-force, low-amplitude stroke can be effectively transmitted to the desired load while isolating or blocking the transmission of the kind of shock waves generated in connection with ground contact in the pile driving operation, by means of a low-impedance gas body or similar capacitive acoustic means employed in accordance with the present invention.

The isolator comprising a low-impedance gas body may be considered as a large acoustic capacitance, as will appear hereinafter, and in practice may consist of a substantial volume of gas confined on each side of a piston means slidably mounted in a closed cylinder so that the cyclic stiffness, or capacitive response, is relatively low, particularly in relation to the above-mentioned high-impedance analogy of the vibratory pile system. This capacitance can be made sufficiently low by having an appreciable "clearance volume" as regards the confine-

ment of the gas between the piston means and the closed portion of the cylinder into which the piston means is operating.

It is therefore an object of this invention to provide novel and improved means for preventing the transmission of undesirable vibratory energy from a pile driver to the supporting and ancillary structure therefor.

It is another object of the invention to provide novel and improved means for decoupling a sonic generator from its supporting structure.

Yet another object of the invention is to provide novel and improved low-impedance capacitive means for isolating a mechanical oscillator from its associated suporting structure.

Still another object of the invention is to provide novel and improved pneumatic apparatus for providing a low-impedance capacitive coupling between vibratory generator apparatus and its associated supporting structure.

An additional object of the invention is to provide novel and improved pile driving apparatus which is substantially free from unwanted transmission of vibration to its supporting structure.

These and other objects of the invention will be more clearly understood upon considering the following description and drawings, in which:

FIGURE 1 illustrates a pile driver system supported by a mobile crane;

FIGURE 2 is a somewhat schematic elevational view of a sonic driver unit of the type to which the present invention applies;

FIGURE 3 is an equivalent circuit analogous to the structure of FIGURE 2, and is useful in the exposition of the invention;

FIGURE 4 is a sectional elevation view of an alternative embodiment of the invention; and

FIGURE 5 is an equivalent circuit analogous to the structure of FIGURE 4.

Looking now at FIGURE 1, the numeral **1** designates a cylindrical pile with its lower end in engagement with the earth **2** and with its upper end carrying a driver unit **4** which may be either a sonic driver unit, as described in the above-mentioned patent, or may be a simple bodily-vibration pile driver unit of well-known construction. The driver unit **4** is lifted into position for operation and supported during the pile driving operation by means of crane **5** and its associated cable equipment (indicated generally at **6**) having a hook **7** engageable with eye **8** of the upper end of the driver unit **4**. The supporting equipment may also be of the type shown in my Patent No. 2,975,846. Pile **1** is shown in the form of a slender cylinder; however, other forms such as H-section steel piles, hollow tubular members, or of other configuration may be used and they may be made of steel, wood, prestressed concrete, plastic, etc. The driver unit **4** is provided with a fitting **9** adapted to receive the upper end portion of the pile **1**. A vertically directed alternating force is transmitted from the driver unit **4** to the upper end of pile **1** through fitting **9** and it is this alternating force which, in the absence of the novel apparatus of the present invention, would transmit the undesired vibration to hook **7**, cable equipment **6**, and the remainder of the supporting equipment.

Looking now at FIGURE 2, the elements comprising a typical sonic driver unit **4** to which the invention may be applied is shown in greater detail together with the novel pneumatic capacitance elements incorporated therein. Extending upward from fitting **9** is a reduced tubular stem **11** which passes through end plate **12**. Plate **12** encloses the lower end of cylindrical body **13**. The driver unit is powered by a pair of electrical motors **14** and **15** fixedly mounted in cylindrical casing **16** which is secured at its lower end to the top of cylindrical body **13**. A central longitudinal bore **17** is provided in body **13** which receives shaft **18** having a small clearance as indicated. Bushings **19** and **20** are fitted in body **13** at each end of bore **17** and support shaft **18** for free vertical sliding movement.

An enlarged bore extends upwardly into the lower end of body **13** and thereby forms a pneumatic cylinder **21** in which piston **22** is slidably mounted. As can be seen in FIGURE 2 piston **22** is mounted on shaft **18** for movement therewith and is also attached to stem **11**. The cylinder **21** is provided with inlet passages **23** and **24** on either side of piston **22**. A gas, preferably air, under pressure is introduced into the cylinder **21** above and below piston **22** via air hoses **25** and **26** which communicate with inlet passages **23** and **24** in body **13**.

Vibration generator **27** comprises the active elements of the driver unit for generating a vertically directed alternating force which is applied to the upper end of stem **11** and therethrough to fitting **9** to the upper end of pile **1** in order to establish either bodily vibration or resonant standing waves therein.

The generator **27** is enclosed within a barrel **28**, the lower end of which is attached to the upper end of shaft **18**. The barrel **28** encloses a series of vertically spaced, fundamental-frequency unbalanced rotors **29–32**, in this case, four in number and in addition, a series of harmonic frequency unbalanced rotors **33–34**, in this case two in number. These rotors are all rotatably mounted on transverse shafts set tightly into the walls of barrel **28**. The rotors **29–34** are driven by motors **14** and **15** through a suitable gear arrangement (not shown). Shaft **35** is provided with a splined section received within an internally splined hollow drive shaft **36** extending downwardly from coupled electric drive motors **14** and **15**. Details of the vibration generator for resonant operation are also shown in the aforementioned Patent No. 2,975,846 as well as my co-pending application Ser. No. 443,997, filed Mar. 30, 1965, entitled Sonic Driver With Pneumatic Capacitance. The pile driving machine itself comprises primarily the vibration generator **27**, the shaft **18**, the stem **11** and the fitting **9**.

The motors **14** and **15** are variable speed electric motors and may be, for example, induction motors driven from a source of variable frequency power, supplied via cables **37** and **38**.

The unbalanced fundamental frequency rotors **29–34** are so phased with relation to one another that all of their unbalanced or eccentric weight portions move up and down in synchronism with one another. The vertical components of force owing to the unbalanced rotors are therefore in phase and additive. The upper and lower rotors **29** and **32** rotate in the same direction, while the two intermediate rotors **30** and **31** rotate in the same direction, but in the opposite direction to the upper and lower rotors. Accordingly, lateral components of force are balanced out.

Likewise, couples tending to rotate generator **27** about a transverse axis are avoided. According to the illustrative arrangement, two double frequency rotors **33** and **34** are used, but it should be understood that for a stronger second harmonic, additional double frequency rotors **33** and **34** may be added. It will be obvious that the number of rotors **29–34** may be increased so that any desired relationship between the forces may be achieved.

In resonant operation, the pile **1** with the sonic driver unit **4** fitted to its upper end is hoisted into position as shown in FIGURE 1. Motors **14** and **15** are energized by means of power furnished through power cables indicated at **37** and **38**. The motors drive the generator shaft **35–36**, rotating the unbalanced rotors **29–34**. This results in a complex vibratory motion being generated in a vertical direction with the force from each unbalanced rotor being exerted through its mounting shaft into the generator barrel **28** and being thence transmitted to the upper end of shaft **18** and from the lower end of shaft **18** to piston **22**. Air under pressure is maintained in the pneumatic cylinder **21** above and below the piston **22** during operation. The casing and the drive motors are supported on the

piston through the body of air under compression in cylinder **21**. The body of air under compression between the piston and the heavy body **13** comprises an acoustical capacitance of very low impedance, permitting relative vertical vibration of vibration generator **27**, shaft **18**, piston **22**, and stem **11** relative to the massive body **13**, casing **16** and the motors **14–15**. The splined driving connection **35–36** permits relative reciprocation at that point.

Motors **14** and **15** may be operated at a speed such as to cause the fundamental frequency rotors **29–32** to generate a vertically-directed alternating force at a frequency which is at the resonant frequency of pile **1** for a longitudinal mode of standing wave vibration of the pile. Usually, and preferably, the frequency of the rotors **29–32** is made such as to generate a half-wavelength standing wave in the pile **1**, so that the pile acts as a "free-free" bar, with velocity antinodes at its ends, and a stress antinode at the midpoint. Under these conditions, and disregarding for the time being the double frequency rotors **33–34**, the two upper and lower half-lengths of the pile alternately elastically elongate and contract in step with one another, the cumulative amplitude of the elastic deformation or displacement, measured from the nodal midpoint of the pile, if it were not for the double frequency rotors **33–34**, would under the circumstances assumed have no substantial vibration. However, the double frequency or second harmonic rotors **33–34** result in a two-component action which combines a second harmonic with the fundamental wave. The second harmonic wave is characterized by a velocity antinode at each end of the pile **1** and at the midpoint thereof, with stress antinodes at the quarter and three-quarter points. Thus, the two half-lengths of the pile elongate and contract with 180° phase difference. This results in a peaked double amplitude motion at the lower end of the pile **1** and such action is especially effective in breaking and penetrating hard formations.

As can be seen in FIGURE 2, there is a very appreciable volume of gas on both sides of the double acting piston **22**, which gas portions are confined within the cylinder **21** formed by the enlarged bore. The volume of gas above the piston **22** is effective to carry the weight of the motors **14–15** and the structure secured thereto; the volume of gas below the piston **22** comes into effect during pulling operations, as above described.

Since the above-described structure comprises a vibrating system exhibiting resonance phenomena, the explanation of the invention may be facilitated by employing a dynamical analogy between a mechanical vibrating system and an electrical network excited by an alternating current. This type of analogy is well known to those versed in the art and is described, for example, in "Dynamical Analogies," published in 1943 by D. Van Nostrand Co., New York, and in chapter 2 of "Sonics," by Heuter and Bolt, published in 1955 by John Wiley and Sons. There is shown in FIGURE 3 a simplified electrical network which is a dynamical analogy of the structure shown in FIGURES 1 and 2.

Due to the widespread familiarity which engineers have with the characteristics and design of electrical circuits, the relationships and functions of the elements comprising the mechanical vibrating system of the present invention may be more easily visualized and analyzed by means of the equivalent circuit described hereinafter.

It should be noted in the mechanical system that the forces acting on the mass are in parallel, while in the electrical system the components of the circuit are in series. If the forces in the mechanical system were in series, then the equivalent electrical system would be put in parallel. This network comprises an equivalent circuit including a generator **41** corresponding to the sonic oscillator or vibration generator **27** and which drives the network comprising series capacitance **42**, series inductance **43** connected between one terminal of capacitance **42** and ground **44**. The remaining terminal of the generator **41** is also connected to ground **44**. The output of generator **41** is energy having a sine waveform, as is desired in the actual mechanical structure, since this will provide optimum energy transfer to the utilization circuit. The inductance **43** comprises the effective load of the generator **41** and in the mechanical system includes the pile **1** itself.

It should be understood that the pile **1** has resistive components such as that attributable to the interface friction or surface wall friction between the pile **1** and the earth **2** into which it is driven as well as a resistance corresponding to the sonic energy radiated from the bottom of the pile. However, for purposes of simplification, the load may be considered as consisting principally of series inductance **43**. If the system is a resonant system, as contrasted with a simple non-resonant or bodily vibratory system, then there will be a series capacitance **45** as shown in the dotted outline **46**.

In the network of FIGURE 3 capacitor **42** has a very low impedance. It is very important to note that the capacitive-response isolator corresponding to capacitor **42** can be located anywhere between the vibratory pile driving mechanism and the support. As shown in FIGURE 2, the pneumatic capacitance provided by piston **22** working in cylinder **21** is in parallel with the vibratory system consisting of vibration generator **27**, shaft **18**, stem **11** and pile **1**. This vibration system consists of one complete vibrating assembly. Such vibrating assembly can be a simple bodily vibration system, as described above, or it can be operated by proper provisions, so as to cause resonance at pile member **1** as described in Patent No. 2,975,846.

It is important to note in the vibrating system that vibration generator **27** is effectively isolated from cable equipment **6** by the interposition of the capacitance means (**21** and **22**). Supporting cable equipment **6** connects to the capacitance by means of bodies **16** and **13**. Body **13** is a cylindrical structure. In this embodiment the support means (eye **8**) is directly connected to the cylinder portion (**21**) of the gas-filled capacitance. Therefore, the vibration system comprising vibration generator **27** is coupled directly to the piston of the capacitive isolator. Obviously, the design could be reversed so that the support means (**8**) is connected to the piston portion of such a capacitive isolator and the vibrating structure (generator **27**) is connected to the cylinder portion. In either embodiment there is a gas-filled capacitor providing low impedance isolation between the vibrating pile and/or its vibrator and the support structure connected thereto.

Looking now at FIGURE 5, there is shown a network analogy of an alternative embodiment of the invention in which the isolating capacitance is connected on the other side of the generator as compared with the network of FIGURE 3. In this construction one terminal of generator **47** is connected to ground **44** through capacitor **48**. In this second embodiment the useful load comprises inductance **51** and there is a series capacitance **52** in those instances in which the pile is driven at its resonant frequency. Low impedance capacitor **48** corresponds to the air spring provided by the compressed air or gas located on each side of a piston within a cylindrical bore.

Looking now at FIGURE 4, there is shown the structure of the alternative embodiment of the apparatus, corresponding to the network of FIGURE 5, in which the low impedance acoustic capacitance is placed in the system between the driver unit and the supporting structure rather than between the motor assembly (which is connected directly to the supporting structure) and the vibration generator assembly as in the embodiment of FIGURE 2. The vibration generator **27'** portion of the driver unit is identical in construction to the vibration generator **27** shown in FIGURE 2. However, in this embodiment shaft **53** connects directly to fitting **9'** and to body **54**. Casing **55** is provided with an enlarged cy-

lindrical bore portion **56** located above motors **14'** and **15'**. This cylindrical bore **56** is functionally analogous to the bore defining cylinder **21** shown in the embodiment of FIGURE 2. Piston **57** is secured to shaft **58** for movement therewith. Shaft **58** is slidably supported by bushing **59** which in turn is secured to top plate **61**. Top plate **61** is secured to the periphery of casing **55**. The upper end of shaft **58** is provided with eye **60** which is adapted to engage a hook. The pile driving machine primarily comprises those elements corresponding to the ones mentioned with reference to FIG. 2 and also includes the body **54**, the casing **55**, and the motors **14'** and **15'**. The above-described structure of the embodiment of FIGURE 4 is analogous to the equivalent circuit shown in FIGURE 5. It is important that the support cable **6** be of fairly low stiffness in order to accommodate the vertical vibratory displacement of the generator **27**. The resonant frequency of the combination comprising the generator **27** and the air spring **21–22** can be adjusted by suitably changing the air pressure supplied to the opposite sides of piston **22** via the air hose connections shown (**25–26** or **25'–26'**).

It can be seen by comparing the equivalent circuits of FIGURES 3 and 5 that the low impedance capacitive element **42** or **48** may be series connected on either side of the generator **41** or **47** since in either instance the supporting structure in the mechanical system is effectively isolated from the active elements indicated by bracket **63**.

It should be understood that the piston and cylinder assembly shown is but an exemplary structure for providing the acoustic capacitance and that various other pneumatic devices or their equivalents could be employed and it is intended that the invention employ all low-impedance acoustical capacitances which will perform this same function.

Summarizing, the large isolation capacitance added by the air spring of FIGURES 2 and 4 isolates the very low frequency component of the generator's output from the suspension or support system. Thus, applying the output directly to the load and preventing it from being coupled into the support system.

While there have been shown and described and pointed out the fundamental novel features of the invention as applied to preferred embodiments, it will be understood that various omissions and substitutions and changes in the form and details of the devices illustrated and in their operation may be made by those skilled in the art, without departing from the spirit of the invention; therefore, it is intended that the invention be limited only as indicated by the scope of the following claims.

What is claimed is:

1. Apparatus for isolating the vibratory system of a vibratory pile driver from unwanted transmission into the structure supporting said vibratory pole driver while driving or extracting a pile, comprising:
- an air spring;
- means for securing one end of said air spring to said vibratory pile driver; and
- means for securing the other end of said air spring to said supporting structure.

2. Apparatus for isolating the vibratory system of a vibratory pile driver from unwanted transmission into the structure supporting said vibratory pile driver while driving or extracting a pile, comprising:
- an air spring;
- means for securing one end of said air spring to said vibratory pile driver;
- means for securing the other end of said air spring to said supporting structure; and
- means for adjusting the stiffness of said air spring to present a low acoustical impedance between said vibrating system and said supporting structure.

3. A low impedance isolator for a vibratory pile driver machine comprising:

- a cylinder secured to said machine;
- a closely fitted piston slidably mounted within said cylinder;
- means for introducing gas under pressure into said cylinder on each side of said piston; and
- means connected to said piston for supporting said cylinder and said machine.

4. A low impedance isolator for a vibratory machine for driving or extracting a pile, comprising:
- a cylinder secured to said machine;
- a closely fitted piston slidably mounted within said cylinder;
- means for introducing gas under pressure into said cylinder on each side of said piston; and
- means for connecting said piston to said pile.

5. In a method of sonically driving an elastic structural member into supporting material, in which a sonic oscillator is acoustically coupled to one end of said member for imparting a sonic wave thereto and thus establish resonant vibration therein, the improvement comprising:
- placing an acoustic capacitance between said sonic oscillator and supporting structure therefor.

6. A low impedance isolator for a vibratory pile driver machine, comprising:
- a cylinder enclosed at one end and having an end wall at the other end with an aperture therein;
- a closely fitted piston slidably supported within said cylinder;
- first means for introducing gas under pressure into said cylinder on one side of said piston;
- second means for introducing gas under pressure into said cylinder on the other side of said piston;
- means for securing the closed end of said cylinder to said pile driver machine; and
- means secured to said piston and extending through said aperture, and in gas-tight relationship therewith, attaching said isolator to a structure for supporting said pile driver machine.

7. A low-impedance shock vibration isolator for a vibratory pile driver machine, comprising:
- a cylinder closed at one end and having a shaft-receiving opening in the other end;
- a closely fitted piston slidably supported within said cylinder;
- first inlet means for introducing gas under pressure into said cylinder on one side of said piston;
- second inlet means for introducing gas under pressure into said cylinder on the other side of said piston;
- means for securing said one end of said cylinder to said pile driver machine;
- a shaft extending through said shaft-receiving opening, and in gas-tight relationship therewith; and
- means for securing said shaft to a structure for supporting said pile driver machine.

8. A low-impedance shock vibration isolator for a vibratory machine for driving a pile, comprising:
- a cylinder having a shaft-receiving aperture at each end thereof;
- a closely fitted piston slidably supported within said cylinder;
- first inlet means for introducing gas under pressure into said cylinder on one side of said piston;
- second inlet means for introducing gas under pressure into said cylinder on the other side of said piston;
- first shaft means connected to said piston and extending through one of said apertures for securing said piston to said vibratory machine; and
- second shaft means extending through said other aperture for securing said piston to said pile.

9. The method of isolating the vibrating system of a vibratory pile driving machine from the support mechanism therefor, comprising the steps of:
- transmitting large cyclic force, low cyclic amplitude vibrations from said vibratory driving machine to

said pile so as to apply vibratory force against the earth;

applying guidance force from said support mechanism to said pile and driving machine; and

directing the force transmission path of said guidance force through a change in acoustic transmission medium, which path includes a medium of substantially lower impedance than the material of said pile;

all in such manner so as to ameliorate the transmission of unwanted vibration from said pile and driving machine to said support mechanism.

10. The method of claim **9** which includes the provision of a confined gas body for said lower impedance material.

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