Oct. 11, 1966 A. G. BODINE 3,277,970

SONIC DRIVER WITH PNEUMATIC CAPACITANCE

Filed March 30, 1965

3 Sheets-Sheet 1

FIG 1

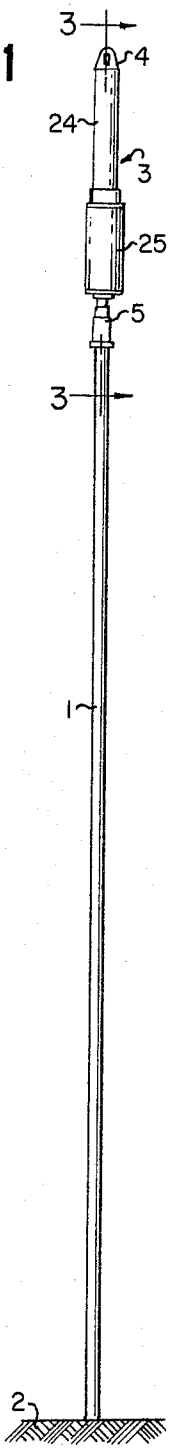



FIG 3

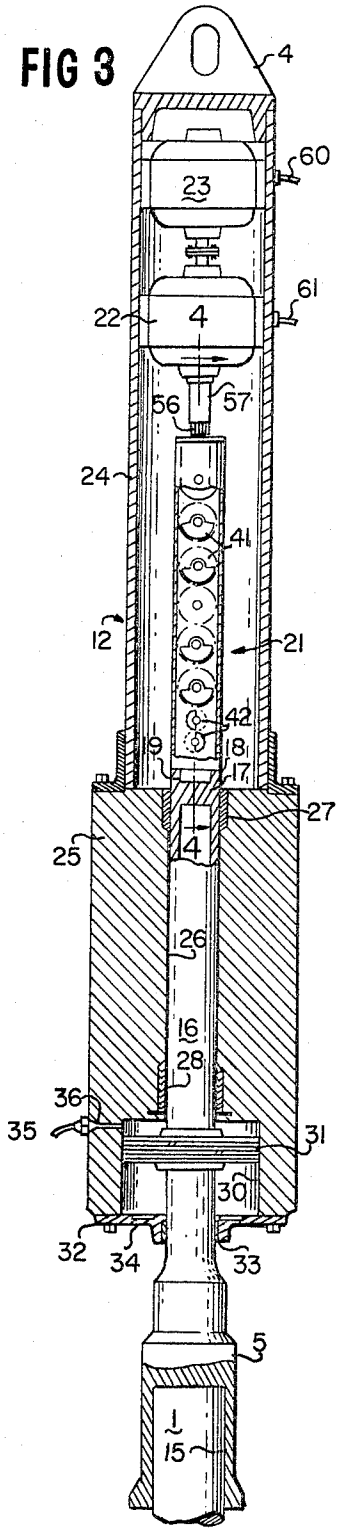
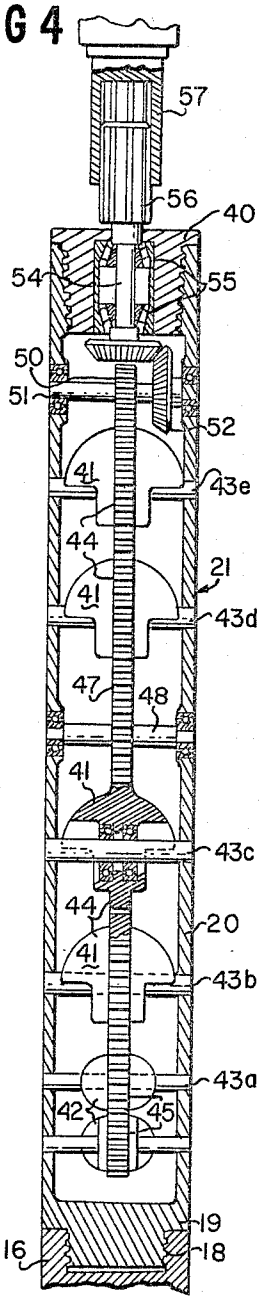



FIG 4




INVENTOR.
ALBERT G. BODINE
BY R. E. Beaugue
ATTORNEY

Oct. 11, 1966 A. G. BODINE 3,277,970

SONIC DRIVER WITH PNEUMATIC CAPACITANCE

Filed March 30, 1965 3 Sheets-Sheet 2

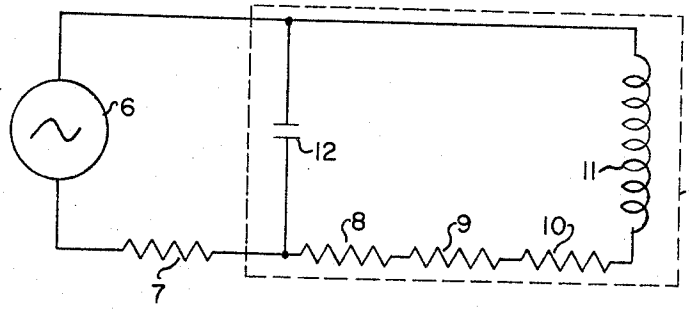



FIG 2

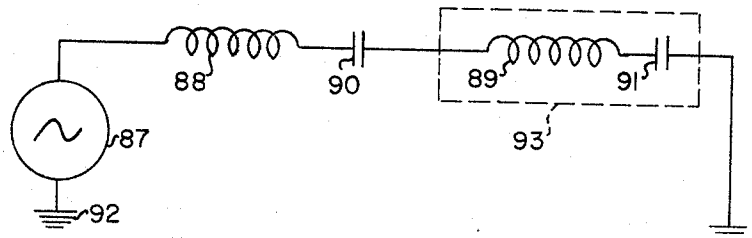



FIG 9

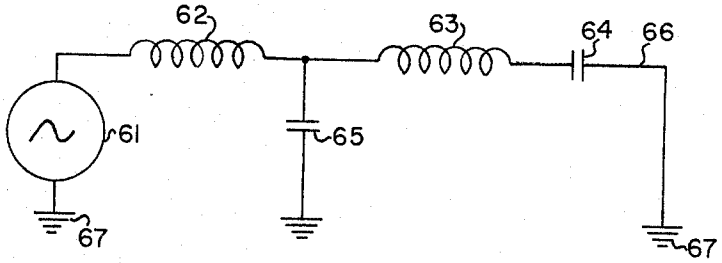



FIG 5

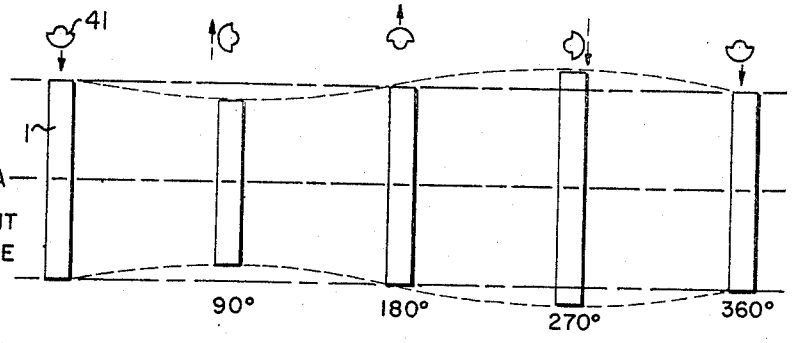



FIG 10

PILE DISPLACEMENT
FUNDAMENTAL WAVE

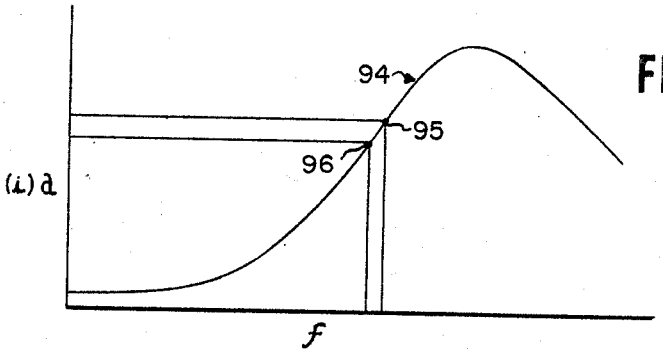



FIG 11

ALBERT G. BODINE
*INVENTOR.*

BY R. E. Beaupre

ATTORNEY

Oct. 11, 1966 A. G. BODINE 3,277,970

SONIC DRIVER WITH PNEUMATIC CAPACITANCE

Filed March 30, 1965 3 Sheets-Sheet 3

FIG 6

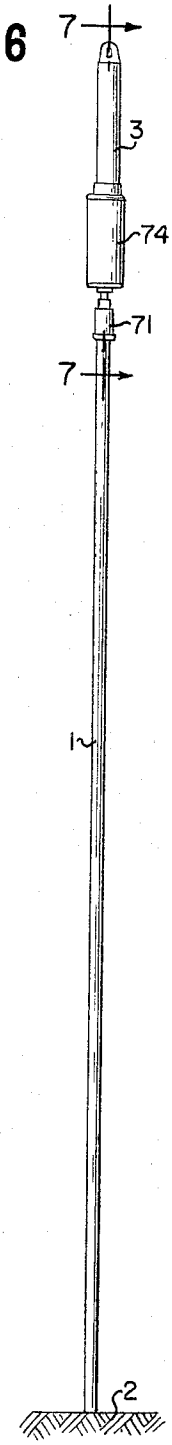



FIG 7

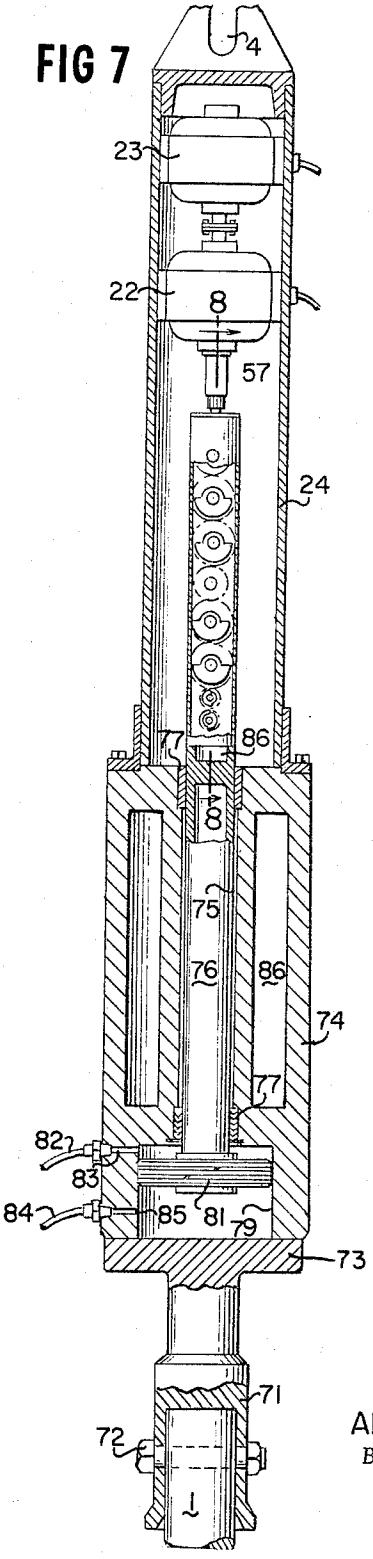
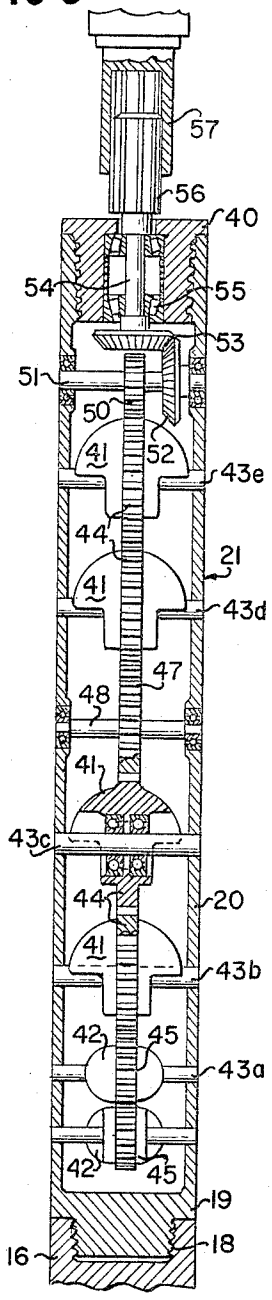



FIG 8




INVENTOR.
ALBERT G. BODINE
BY R. E. Beaugue
ATTORNEY

United States Patent Office

3,277,970

Patented Oct. 11, 1966



# 3,277,970
# SONIC DRIVER WITH PNEUMATIC CAPACITANCE

Albert G. Bodine, 7877 Woodley Ave., Van Nuys, Calif.

Filed Mar. 30, 1965, Ser. No. 443,997
4 Claims. (Cl. 175—19)

This invention, which is a continuation-in-part of co-pending application Serial No. 183,608 filed March 29, 1962, now U.S. Letters Patent 3,193,027, relates generally to sonic driving methods and apparatus, and more particularly to such methods and apparatus as may be employed for driving piles, such as are used for buildings or other structural foundations.

There has been disclosed in my patent entitled "Acoustic Method and Apparatus for Driving Piles," Patent No. 2,975,846 and my co-pending application Serial No. 710,956, filed January 24, 1958 entitled "Apparatus for Driving Piles" now U.S. Letters Patent 3,054,463 and in my co-pending application Serial No. 183,608, filed March 29, 1962 entitled "Acoustic Method for Driving Piles," now U.S. Letters Patent 3,193,027, method and apparatus for driving piles into either dry surface earth, marsh or tidewater ground, or in underwater situations. The piles may be those conventionally used, steel H-section members, members of corrugated section, tubular section, or of other shape, and may be composed of steel, wood, prestressed concrete, plastic, etc. All of these disclosures relate to means whereby a pile is driven into the terrain by means of an elastic wave generator acting on the upper end of the pile to establish a standing wave vibration in the pile, and causes it, when resting on the earth, to be driven downwardly therein. The pile initially vibrates as a "free-free" bar with a velocity antinode at each end, and a node at the midpoint. The pile, undergoing such standing wave action, alternately undergoes elastic elongations and contractions. This will cause the lower end of the pile to sonically activate the earth whereupon it will more easily be driven downwardly and penetrate the earth. One or more additional velocity antinodes may appear along the pile, depending upon harmonic wave frequencies generated in relation to the length of the pile. Such additional antinodes maintain the pile in active vibration at spaced locations along its length and are thus useful in reducing static friction between the embedded length of the pile and the surrounding earth. Such reduction in static friction will, of course, greatly facilitate the penetration of the pile into the earth.

In pile driving machines of the type under discussion, where substantial power is desired, practical considerations require an elastic wave generator or "sonic oscillator" of substantial size and weight. The mass of the oscillator itself is a detriment to efficient operation. Since the oscillator is used to drive a resonant earth-penetrating member, it would be desirable to have the mass of the oscillator tuned out by the elastic reactance of the pile itself. If the mass of the oscillator is a large fraction of the mass of the pile, then the oscillator will function as if it were an extension of the upper end of the pile or that portion of the pile at which the oscillator is attached. This effect is undesired since a heavy oscillator will cause the node to move closer to the oscillator. That is, the oscillator behaves as if it were a substantial length of inertia of the pile and will thereby tend to lower the resonant driving frequency.

When the node is relatively close to the oscillator, the oscillator is required to move with a relatively short stroke and is therefore not capable of transmitting as much power to the pile as it would if it were at a low impedance region where the amplitude of the cyclic



stroke is relatively large. Thus, it becomes desirable to employ some means to tune out a significant part of the mass of the oscillator and thereby increase the resonant frequency of the complete circuit. This objective is accomplished by means of the present invention wherein the oscillator is made to appear as having a decreased mass by means of an added capacitance which is acoustically coupled to the system in such a manner as to tune out part of the mass of the oscillator. In a preferred construction, this capacitance is implemented by a pneumatic element. The added capacitance may be coupled into the system in either a parallel or a series manner, as will appear hereinafter.

It is therefore an object of the invention to provide a novel and improved method, and apparatus therefor, which will increase the efficiency of sonic driving apparatus.

Another object of the invention is to provide novel and improved sonic driver apparatus having a pneumatic capacitance coupled to the resonantly driven system.

Yet another object of the invention is to provide a novel series pneumatic capacitance for coupling a sonic oscillator to a resonantly driven member.

It is still another object of the invention to provide a novel parallel pneumatic capacitance for coupling a sonic oscillator to a resonantly driven pile.

Still another object of the invention is to provide a novel means and method for tuning out the effect of the mass of a sonic oscillator in a sonic driving system.

A general object of the invention is to provide novel and improved sonic pile driving apparatus which overcomes disadvantages of previous means and methods heretofore intended to accomplish generally similar purposes.

Although certain features of the invention may be applied to various types of sonic pile driving apparatus such as disclosed in my above-mentioned prior patents, it will be convenient to describe the invention in connection with a sonic pile driver of the type employed to drive a single column symmetrical pile. Having gained an understanding of this form of the invention, persons skilled in the art will appreciate the manner in which the features of the invention may be employed in other sonic driver devices such as employed for driving nonsymmetrical structures, etc.

It is to be understood that inasmuch as the sonic oscillator itself does not constitute part of the instant invention, only so much of the structural details and operational features thereof considered to be essential for a complete understanding of the present invention are described herein. A complete description of a suitable sonic oscillator may be found in my Patent No. 2,960,314 entitled "Method and Apparatus for Generating and Transmitting Sonic Vibrations."

The present invention itself, both as to its organization and manner of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in which like reference characters refer to similar parts, and in which:

FIGURE 1 is a somewhat schematic elevational view of a sonic pile driving system constructed in accordance with the invention, and in which equipment for lifting the system into position for operation has been omitted from the drawing in the interest of clarity;

FIGURE 2 is an equivalent circuit useful in the exposition of the invention;

FIGURE 3 is a sectional view taken along line 3—3 of FIGURE 1;

FIGURE 4 is a sectional view taken along lines 4—4 of FIGURE 3;

FIGURE 5 is an equivalent circuit diagram which is analogous to the embodiment of the invention shown in FIGURES 1, 3 and 4;

FIGURE 6 is an elevational view of an alternative embodiment of the invention;

FIGURE 7 is a sectional view taken along line 7—7 of FIGURE 6;

FIGURE 8 is a sectional view taken along line 8—8 of FIGURE 7;

FIGURE 9 is an equivalent circuit diagram which is analogous to the embodiment of the invention shown in FIGURES 6–8;

FIGURE 10 is a chart which graphically illustrates wave action generated in a pile, in accordance with the invention;

FIGURE 11 is a chart which graphically illustrates the frequency versus amplitude characteristics of the sonic driving apparatus of the invention.

In FIGURE 1 the numeral **1** designates generally a cylindrical pile, with its lower end in engagement with the earth **2**, and with its upper end carrying sonic oscillator **3** constructed in accordance with the invention. Equipment for hoisting the apparatus into the position shown, and for suspending it in such position during use, has been omitted from FIGURE 1 in the interest of clarity. It will be understood, however, that any suitable hoisting equipment such as a crane with block and tackle equipment, functioning with a hook engageable with an eye **4** at the upper end of the sonic driver may be used. Suitable equipment of this nature is 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 may also be used, provided only that they have sufficient elasticity to permit standing wave action therein.

The sonic oscillator **3** is provided with a fitting **5** adapted to receive the upper end portion of the pile **1**. A vertically-directed alternating force is transmitted from oscillator **3** to the upper end of pile **1** through fitting **5**, which is capable of resonating the pile **1**. Since this structure comprises a vibrating system exhibiting resonance phenomena, it is useful to employ a dynamical analogy between the mechanical vibrating system and an electrical circuit 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" by Harry F. Olson, published in 1943 by D. Van Nostrand Co., New York, and in chapter 2 of "Sonics" by Hueter and Bolt, published in 1955 by John Wiley & Sons.

There is shown in FIGURE 2 a basic equivalent electrical circuit of apparatus of the type shown in FIGURE 1. This equivalent circuit comprises a generator **6** corresponding to the sonic oscillator **3** and which drives a network comprising series resistances **7–10**, shunt inductance **11**, and shunt capacitance **12**. The output of generator **6** is energy in the form of a sine wave, as is desired in the actual mechanical structure, since this will provide optimum energy transfer to the utilization circuit. The load comprises the network indicated at **13** all of which corresponds to the pile **1**. Network **13** comprises series resistances **8–10**, shunt capacitance **12**, and shunt inductance **13**. Resistance **7** corresponds to frictional losses between the oscillator **3** and the pile **1**. Resistance **8** corresponds to the internal damping in the pile **1**. The interface friction or surface wall friction between the pile **1** and the earth **2** into which it is driven corresponds to resistance **9**. Resistance **10** corresponds to the radiated sonic energy, most of which is radiated from the bottom of the pile **1**. Shunt capacitance **12** corresponds to the elastic stiffness reactance of the pile **1** exhibited at the pile antinodes. All of the velocity antinodes of the mechanical system, of which there are two or more under most practical conditions, behave as a lumped inductance and correspond to inductance **11**. Due to the widespread familiarity which engineers have with the characteristics and design of electrical circuits, the relations and actions of the elements comprising the mechanical vibrating system of the present invention may be more easily visualized and analyzed by means of equivalent circuits such as described above.



Looking now at FIGURE 3, the elements comprising the sonic oscillator will be described in greater detail, and the novel pneumatic capacitance elements incorporated therein will also be described in terms of an equivalent circuit. Extending upward from fitting **5** is a reduced tubular stem **16**, closed at its upper end, as indicated at **17**, and formed at the top with a threaded socket **18** into which is screwed a threaded coupling member **19**, formed on the lower end of the cylindrical hollow body or barrel **20** of vibration generator **21**. Generator **21** is driven from a pair of electric motors **22** and **23** fixedly mounted in a cylindrical casing **24**, which is tightly mounted at its lower end on top of a heavy cylindrical body **25**, provided with a central longitudinal bore **26** which receives the aforementioned stem **16** with a small clearance as indicated. A bearing bushing **27** fitted in body **25** at the upper end of bore **26** supports stem **16** for free vertical sliding movement, and at the lower end of the body **25**, a packing unit **28** is mounted for packing the stem **16**.

Enlarged bore **30** extends upwardly into the lower end of body **25** and forms a cylinder in which is mounted sliding piston **31**. Piston **31** is mounted on stem **16** for movement therewith. The lower end of the cylinder is closed by a bottom plate **32**, in turn secured to the lower end of body **25**. This bottom plate **32** is provided with a bearing bushing **33** slidably supporting stem **16** below piston **31** and is provided also with an air vent hole **34**. Air under pressure is introduced to the cylinder surface above piston **31** via air hose **35** and passage **36** in body **25**.

Vibration generator **21** comprises the active elements of the sonic oscillator for generating and applying to the upper end of stem **16**, and thence, through fitting **5** to the upper end of pile **1**, a vertically-directed alternating force capable of resonating the pile **1**.

The generator includes the aforementioned barrel **20**, screw coupled at its lower end to the upper end of the aforementioned stem **16**. The upper end of barrel **20** is closed by means of a closure or plug member **40**. The barrel **20** enclosed a series of vertically spaced, fundamental frequency unbalanced rotors **41**, in this case, four in number, and in addition, a series of harmonic frequency unbalanced rotors **42**, in this case two in number. These rotors are all rotatably mounted on transverse shafts **43***a* through **43***e* set tightly into the walls of barrel **20**. The rotors **41** include intermeshing gears **44**, and the rotors **42** include intermeshing gears **45**. In the illustrative embodiment, the rotors **41** are separated into two upper rotors and two lower rotors, interconnected by an idler gear **47** on a shaft **48** rotatably mounted in suitable bearings in the walls of barrel **20**. The gear **45** of uppermost rotor **42** meshes with the gear of the lowermost rotor **41**. Gears **45** of harmonic frequency rotors **42** are half the diameter of the gears **44** for fundamental frequencies **41**, so that rotors **42** turn at twice the angular velocity as rotors **41**, and are therefore of double or second harmonic frequency.

Gear **44** for uppermost rotor **41** is driven by pinion **50** on rotatable shaft **51**, carrying a bevel gear pinion **52** driven from bevel gear **53** on vertical shaft **54**. Shaft **54** is supported by suitable bearings **55** mounted within plug member **40**, and being provided above the latter with a splined section **56** received within an internally splined hollow drive shaft **57** extending downwardly from coupled electric drive motors **32** and **23**.

The motors **22** and **23** are variable speed electric motors and may be, for example, induction motors driven from a source of variable frequency power. This source may, for example, comprise a generator having as its prime mover a variable-speed gas engine. In some instances an ordinary induction motor will have enough

"slip" so that it can be driven by a regular 60-cycle or other suitable fixed frequency source.

The unbalanced fundamental frequency rotors **41** 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.

It will be seen that the upper and lower rotors **42** rotate in the same direction, while the two intermediate rotors **41** 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 **21** about a transverse axis are avoided. According to the illustrative arrangement, two double frequency rotors **42** are used, but it should be understood that for a stronger second harmonic, additional double frequency rotors **42** may be added. Due to the half size of the rotors **42**, as compared with the rotors **41**, necessitated by the half size gears **45**, the forces contributed by the individual rotors **42** will be slightly less than the forces contributed by the rotors **41**, even though the smaller rotors operate at twice the centrifugal speed. It will be obvious that the number of rotors **42** may be increased so that any desired relationship between forces generated by the rotors **41** and the rotors **42** may be achieved. It is evident that by a suitable increase in the number of rotors **42**, the total force exerted thereby may, for example, be made equal to the total force generated by the rotors **41**. The rotors **42** are phased to move vertically in synchronism with one another, so that the vertical components of force will be additive whereas the horizontal components of force will be cancelled.

In order to drive a pile, the pile **1** with the sonic oscillator fitted to its upper end, is hoisted into the position shown at FIGURE 1. Motors **22** and **23** are energized through power furnished via conductors indicated at **60** and **61**. The motors drive the generator shaft **56**, rotating the unbalanced rotors **41** and **42**. This results in a complex alternating force being generated in a vertical direction, the force from each unbalanced rotor being exerted through its mounting shaft onto the generator barrel **20**, and being thence applied to the upper end of stem **16**, and from the lower end of stem **16** through fitting **5** to the upper end of the pile **1**. Air under pressure is maintained in the piston chamber above the piston **31** during operation, and it will be seen that the weight of the massive body **25**, the casing **24**, and the drive motors **22** and **23**, is supported on the piston **31** through the body of air under compression above the latter. This weight is transferred from piston **31** to stem **14** and fitting **5** and thence to the upper end of the pile **1**, whereby the pile **1** is biased downwardly by a substantial weight. The body of air under compression between the piston **31** and the heavy body **25** thus acts as an air spring, permitting relative vertical vibration of vibration generator **21**, stem **16**, fitting **5** and the upper end portion of the pile **1** relative to the massive body **25**, casing **24** and the motors **22** and **23**. The splined driving connection at **56**, **57** permits relative reciprocation at that point.

Motors **22** and **23** are operated at a speed such as to cause the fundamental frequency rotors **41** to generate a vertically-directed alternating force at a frequency which is a resonant frequency of pile **1** for a longitudinal mode of standing wave vibration of the pile. Usually, and preferably, the frequency of the rotors **41** 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 **42**, 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, progressively increasing toward each end. The midpoint of the pile, if it were not for the double frequency rotors **42**, would under the circumstances assumed have no substantial vibration.

The operation of the sonic oscillator and the effect of a harmonic wave in combination with the fundamental frequency wave will be discussed in greater detail in a subsequent section of this specification which relates to FIGURES 10 and 11. Having described the structure of the sonic oscillator and the general manner in which it coacts with the pile, it will now be convenient to analyze this structural combination in terms of its equivalent circuit. As was mentioned previously, it is desirable to employ some means to tune out part of the mass of the sonic oscillator in order to move the vibratory node of the pile away from the oscillator. One way of accomplishing this is by coupling a "capacitance" in parallel with the pile and the oscillator. This can be illustrated by means of the circuit diagram of FIGURE 5. Generator **61** drives the network comprising series inductances **62** and **63**, series capacitance **64**, and shunt capacitance **65**. The pile itself corresponds to the series combination **66** of inductance **63** and capacitance **64**. The distributed resistance elements, as described in connection with FIGURE 2, have been omitted in order to simplify the explanation of the matching of the load to the generator. The series inductance **62** corresponds to the mass of the sonic oscillator **3** of FIGURE 1, and both the oscillator and the load (viz. the pile **1**) are referenced to ground **67**. In the absence of capacitance **65**, inductances **62** and **63** would appear as a lumped inductance which would correspond to the mass of the vibration generator **21** appearing as an artificial extension of the upper end of the pile **1** itself. By placing capacitance **65** in parallel with the combination of the generator **61** and inductance **62**, inductance **62** may effectively be tuned out, and only the impedance of the series combination **66** will appear as a load across generator **61**.

In the mechanical system, the equivalent of parallel capacitance **65** is provided by an air spring located between the end of the pile **1** and the relatively stationary mass of body **25**. In practice the relatively stationary mass may also include the prime mover (motors **22** and **23**) and the associated structure on which the prime mover is mounted. This heavy auxiliary mass is the equivalent of ground **67** so that the capacitance provided by the air spring can be placed, acoustically, between this ground and the upper end of the pile. The result then is that the capacitance provided by the air spring functions to tune out a substantial part of the mass of the end of the pile, which includes the undesirable mass of the sonic oscillator body and supporting structure.

Comparing FIGURE 5 to the structure of FIGURE 3, capacitance **65** is the equivalent of piston **31** working against the air in bore **30**.

There is shown in FIGURES 6–8 an alternative embodiment of the invention in which the undesired mass of the sonic oscillator is tuned out by means of a series capacitance. The vibration generator portion of the apparatus is substantially identical to that described above in connection with FIGURES 1, 3 and 4, and like reference numbers correspond to like parts in the several views. The principal difference between the apparatus of FIGURES 3 and 4, and that of FIGURES 7 and 8, is with respect to those elements located between the lower end of casing **24** and the upper end of the pile **1**.

Looking now at FIGURE 6, this embodiment of the apparatus comprises sonic oscillator **3** which is coupled to the apparatus contained within body **74**. The lower end of body **74** is provided with fitting **71** adapted to receive the upper end portion of the pile **1**.

Looking now at FIGURE 7, the sonic oscillator **3** and the elements within body **74** are shown in greater detail. Pile **1** may be secured to fitting **71** by means of a suitable fastener **72**. Extending upward from fitting **71** is an in-

tegral section which terminates in bottom plate **73**. Plate **73** is attached to the lower end of the hollow cylindrical body **74** by any suitable means, as by welding for example. Body **74** is provided with a central longitudinal bore **75** through which extends shaft **76**. A bearing bushing **77**, fitted in body **74** at the upper end of bore **75**, supports shaft **76** for free vertical sliding movement. Near the lower end of body **74** there is provided a packing unit **78** for packing shaft **76**. A large cylindrical bore **79** extending upwardly into the lower end of body **74** provides a cylinder in which works piston **81** fixedly mounted to the lower end of shaft **76**. Air under pressure is introduced into the cylinder above piston **81** via air hose **82** and passageway **83** in body **74**. Air under pressure is also introduced into the cylinder below piston **81** via air hose **84** and passage **85** in body **74**.

Body **74** may be provided with an internal cavity **86** to minimize the mass at the upper end of the pile. As can be seen in FIGURE 7, the cylindrical body **74** comprises a fairly massive structure which is coupled to the upper end of the pile **1**. In order to keep this assembly as light as possible the cavity **86** is provided. Furthermore, the body **74** may be fabricated from aluminum or other relatively lightweight material. The lower end of barrel **20** is screw coupled to the upper end of shaft **76** by means of threaded socket **86**. Sine wave vibratory motion generated by the rotors within the sonic oscillator impart a cyclical upward and downward motion to shaft **76**. The motion of shaft **76** is imparted to piston **81** which in turn works against the air spring in cylindrical bore **79** on either side of piston **81**. The acoustic energy imparted to piston **81** is coupled through the elastic reactance (capacitance) of the air spring to body **74** and bottom plate **73**, from which it is transmitted to fitting **71**. The vertically directed alternating force imparted to fitting **71** is capable of resonating the pile **1**.

Upon consideration of the equivalent circuit shown in FIGURE 9, which is analogous to the above-described structure of FIGURES 6–8, it will be seen that the capacitance supplied by the air spring (elements **79–85**) is in series relationship with the sonic oscillator **3** and the load consisting of the pile **1**. The equivalent circuit comprises generator **87** which drives the network comprising inductances **88** and **89**, and capacitances **90** and **91**, all of which are in series. Generator **87** is referenced to ground **92**, as is one terminus of the series network. The portion of the network consisting of inductance **89** and capacitance **91**, enclosed within the dotted outline **93**, comprises the useful load and corresponds to the pile **1** in the apparatus of FIGURES 6–8. Inductance **88** corresponds to the mass of the sonic oscillator.

As can be seen, the output of the generator **87** is coupled to the useful load **93** through a series capacitance **90**. This capacitance **90** corresponds to the series air spring **79–85** of the apparatus of FIGURE 7. This arrangement accomplishes the same objective as the parallel capacitance of the above-described embodiment of FIGURE 3. As in the previous embodiment, the capacitance is in the form of a piston **81** working in a cylinder **79** and the oscilator **3** is coupled to the piston **81**. However, in this instance the cylinder **79** is coupled to the end of the pile **1** and receives the reaction due to its resonance with the oscillator **3**, working as a separate circuit in combination with the air-spring capacitance. This air spring capacitance is provided by the compressed air body located on each side of the piston **81** within the cylindrical bore **79**. In this embodiment, it is desirable to tune the mass of the oscillator and the stiffness of the capacitance so that it will be near the resonant frequency of the pile **1**, itself.

In operation, the resonant frequency of the pile **1** is approached somewhat by the resonant frequency of the oscillator and of its air spring. At this point it should be mentioned that the resonant frequency of the pile includes the mass comprising the above-mentioned cylinder body **74** and the electric motors enclosed within casing **24** up to and including the eye **4** where the support cable is to be connected. Moreover, it is important that the support cable be of fairly low stiffness to accommodate the vertical vibration of the complete assembly. The resonant frequency of the oscillator and its piston can be adjusted by suitably changing the air pressure supplied to the opposite sides of piston **81** via the air hose connections shown.

Having described the two embodiments of the invention, the manner in which the standing wave is set up in the pile will now be considered in further detail. Looking at FIGURE 10 there is shown one of the synchronized rotors **41** over the pile **1** in each of five conditions of the cycle under which the pile operates.

For simplicity a typical case is assumed wherein pile motion is in phase with motor force.

The solid arrows below the representations of the rotor represent the direction of the force exerted by the rotor on the pile **1** in that position. The dotted arrows indicate the components of vertical velocity of the rotors. The alternating force exerted on the pile, at the fundamental frequency for half-wavelength standing wave vibration of the pile, causes the pile to alternately elastically contract and elongate, as represented in the five successive pile positions shown. It will be observed that the vertical force wave lags the vertical component of rotor velocity by 90°. Thus, for example, at the 90° position, the rotor is rising at maximum velocity, but the vertical force exerted thereby is zero. At 180°, the rotor is at the top, exerting a maximum upward force component (by reason of its centrifugal force), while its vertical component of velocity is zero. It will further be seen that the longitudinal displacements of the pile lag the vertical force wave by 90°. Thus, in the first position, the rotor **41** is at the bottom, exerting a maximum downward force, the vertical velocity of the rotor is zero, and the pile is at its normal length, but is contracting at maximum velocity. In the second position, 90° later, the rotor is rising at maximum velocity, vertical force is zero, the pile is contracted to its minimum length, and is momentarily at zero vertical velocity. The conditions for the third, fourth and fifth positions will be readily understood from the diagrams.

An advantage of the apparatus of the type disclosed is that they may be made to handle substantial power by providing a high Q factor. This term, widely applied to the analysis of circuits of the kind shown in FIGURES 2, 5 and 9, may be defined as the ratio of energy stored to energy dissipated per cycle. Thus, with a high Q factor, the sonic system can store a high level of sonic energy, to which a constant input and output of energy is added and subtracted, respectively. In an electrical circuit, the Q factor is numerically defined as the ratio of inductive reactance to resistance. Moreover, a high-Q system is dynamically active, giving considerable cyclic motion where such motion is needed.

There is shown in FIGURE 11 a Q curve wherein displacement or velocity amplitude (corresponding to current in an equivalent electrical circuit) is indicated along the axis of the ordinate and is identified as *a*. Frequency in cycles per second is plotted along the axis of the abscissa. The oscillator is capable of operating at some frequency in excess of the resonant frequency of the pile, say 100 cycles per second. However, as the frequency increases from zero towards 100 cycles per second it will reach the step slope of the curve indicated at **94**. As can be seen, when the frequency reaches, say 80 cycles per second, as indicated by point **95**, a very small change in frequency will result in a relatively large change in amplitude. This change in amplitude is reflected as a correspondingly large change in torque at the prime mover. As a consequence of this large change in torque the oscillator will be loaded down, thus causing the frequency to decrease as indicated at point **96**. The resulting decrease

in frequency will result in a relatively large reduction in velocity amplitude and an attendant reduction in torque. This reduction in torque is seen as a decrease in the load on the prime mover. Thus, the frequency tends to again increase towards point **95**. The result of this sequence of events will cause the oscillator to "lock in" at some frequency corresponding to a point of equilibrium on the steep portion **94** of the Q curve.

In this way, the oscillator tends to automatically operate at the resonant frequency of the system.

Summarizing, the capacitive reactance added by the parallel air spring of FIGURES 3 and 4 and the series air spring of FIGURE 7 prevents the inertia of various necessary bodies or masses in the system from operating to the detriment of the process. That is, since the sonic oscillator or vibration generator must necessarily have a supporting structure with some inherent mass, there will be, even when minimal, an undesired mass of inertia. This inertia is a force-wasting detriment, acting as a blocking impedance using up part of the periodic force output just to accelerate and decelerate the supporting structure. By the use of an elastically vibrator structure in the system, in accordance with the present invention, the effect of this mass or the mass reactance resulting therefrom, is counteracted at the frequency of resonance; and, when a resonant acoustic circuit is thus used, with adequate capacitance (elastic reactance) these blocking impedances are tuned out of existence, at resonance, and the periodic force generating means can deliver its full impulse to the load, comprising the resistive component of the impedance.

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 driving a structural element into supporting material comprising:

an elongated elastic structure;

generator means for generating longitudinal elastic waves at the resonant frequency of said elastic structure, said elastic structure being drivingly coupled to said generator means, so as to be loaded thereby; and

acoustic capacitance means coupled to said elastic structure and to said generator means, for increasing the efficiency of acoustic energy transmission between said generator means and said elastic structure.

**2.** Apparatus as defined in claim **1** wherein said acoustic capacitance means comprises:

an air spring connected in series with said generator means and said elastic structure.

**3.** Apparatus as defined in claim **2** wherein said acoustic capacitance means comprises:

a supporting body for said generator means; and

an air spring coupled between said generator means and said supporting body.

**4.** Apparatus for driving a pile into the earth, comprising:

an elongated pile of fixed length;

an elastic vibration generator attached to said pile, said generator embodying a mechanical vibrator having a fixed driving connection to said pile, said vibrator being capable of applying cyclic longitudinal vibration forces to said pile at the longitudinal resonant elastic vibration frequency of said pile; and

an air spring drivingly coupled to said generator and to said pile to transmit forces from said generator to said pile.

**References Cited by the Examiner**

UNITED STATES PATENTS

| | | | |
|---|---|---|---|
| 2,942,849 | 6/1960 | Bodine | 175—55 |
| 3,195,659 | 7/1965 | Goodman | 175—55 |

CHARLES E. O'CONNELL, *Primary Examiner.*

R. E. FAVREAU, *Assistant Examiner.*