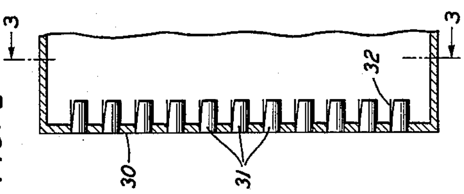
Nov. 21, 1950 W. P. MASON 2,531,230

ELECTRIC POWER SOURCE

Filed March 16, 1946 2 Sheets-Sheet 1

FIG. 2



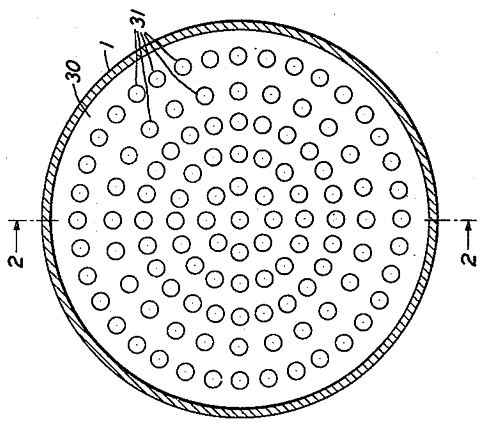
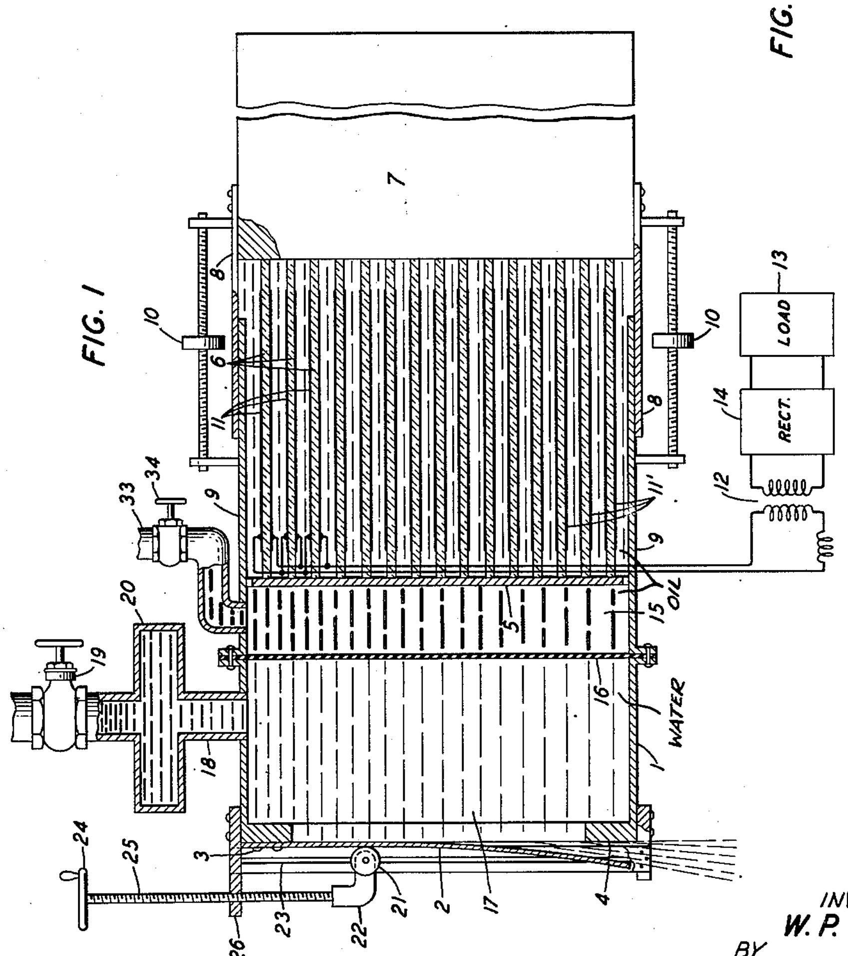


FIG. 3

FIG. 1



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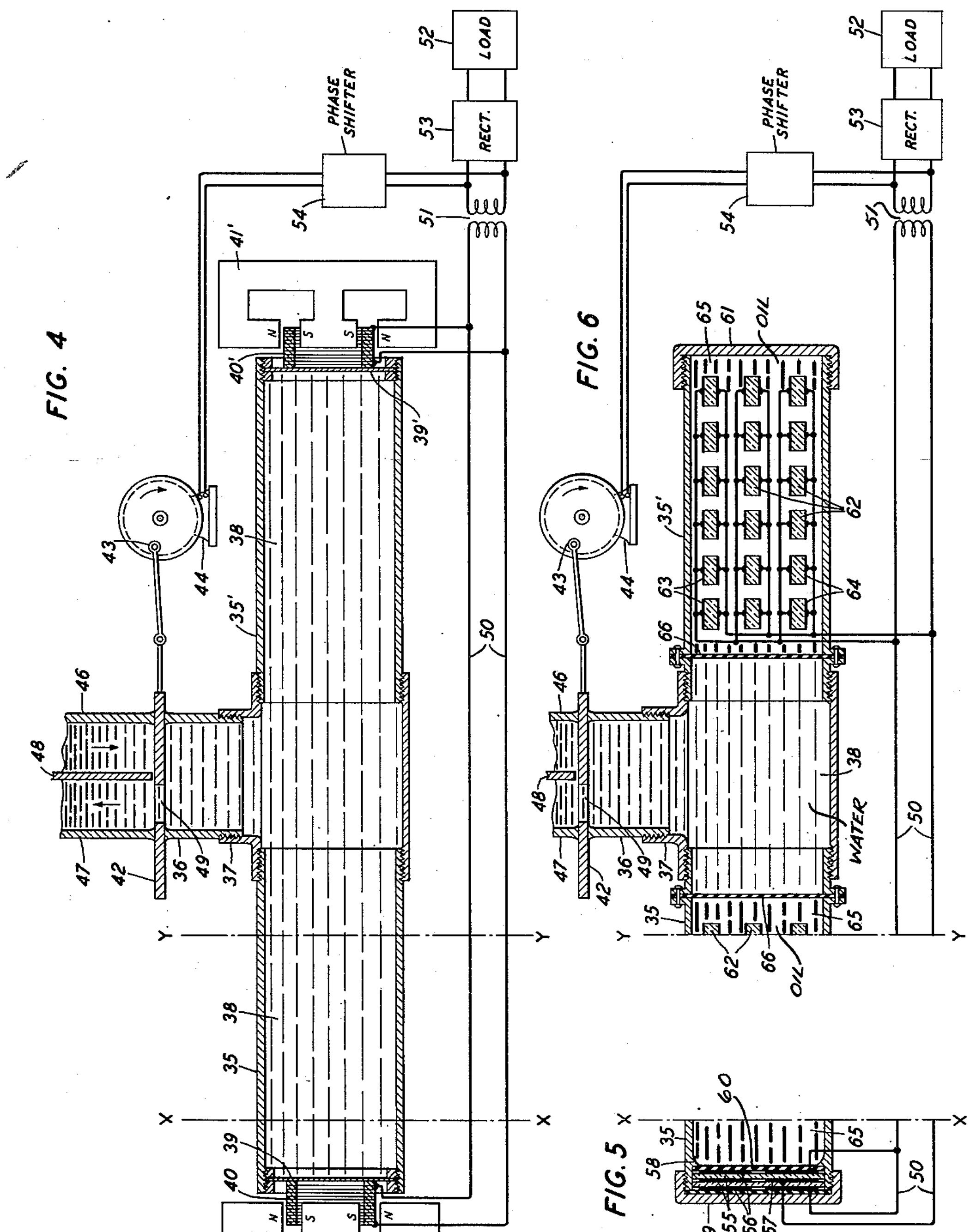

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2,531,230

ELECTRIC POWER SOURCE

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4 Claims. (Cl. 290—1)

1

This invention relates to prime sources of energy and more particularly to a novel system for producing electrical or vibratory energy from the gravitational energy of a hydrostatic pressure head.

An object of the invention is to convert hydrostatic energy into electrical energy in a direct and simple manner.

Another object of the invention is to convert hydrostatic energy into hydrodynamic energy of vibration.

Another object of the invention is to produce electrical energy without the use of massive rotating mechanical parts.

Still another object of the invention is to utilize the energy of high frequency pressure waves to excite an electromechanical transducer such as a piezoelectric element.

The phenomenon known as "water hammer" has been known for generations. It has generally been regarded as an annoyance to be tolerated or as a difficulty to be circumvented by the ingenuity of hydraulic engineers. It has been put to practical use in one instrumentality, the water ram, wherein the sudden closure of a valve in a pipe in which water is flowing combines with the inertial mass of the flowing water to raise a portion of the water to a higher level. This device is in general very wasteful of water, makes no use of the transitory high frequency wave energy which follows the shock of valve closure, and is, furthermore, restricted to comparatively low frequency operation.

In accordance with the invention in one of its aspects the water hammer principle is embodied in a new instrumentality of greater efficiency, while in another aspect the considerable available high frequency water hammer energy is converted into electrical energy to be supplied to any desired load. In still another aspect, principles which have long been well known in the wind musical instrument art are taken over and applied to the hydraulic art and to the art of power generation with consequently greatly improved efficiency due to the difference between the characteristics of the liquid medium and those of the air or gas medium.

In accordance with the invention a fluid such as water is intermittently admitted to and discharged from a vessel containing a resonant chamber by way of a rapidly oscillating valve, giving rise to oscillating pressures within the chamber. By the proper dimensioning of the component parts the chamber is made resonant at the desired frequency so that dynamic pres-

2

sures of substantial magnitudes are built up. The resonant chamber is coupled to a suitable mechanical-electrical transducer such as a piezoelectric element which, when actuated by the pressures in the resonant chamber, behaves as a generator of electric current which may be drawn off and supplied to a load. Thus a simple and direct conversion is effected, first from hydrostatic energy of a liquid column into hydrodynamic energy of pressure waves, while the latter is then in turn converted into electric energy by the high frequency pressure responsive transducer.

The invention will be fully understood from the following detailed consideration of some preferred embodiments thereof, taken in conjunction with the appended drawings, in which:

Fig. 1 is a sectional diagram of the apparatus and a schematic diagram of the electrical circuit of a vibratory system for converting hydrostatic energy into electrical energy;

Fig. 2 is a sectional diagram of a modified arrangement of a part of Fig. 1;

Fig. 3 is a partial end view taken on line 3—3 of Fig. 2, being principally, however, a diagrammatic showing of the relationships of the nozzles, and of the cross-sectional shape of the chamber carrying said nozzles;

Fig. 4 is a sectional diagram of the apparatus and a schematic diagram of the electric circuit of a modification of Fig. 1 adapted principally for operation at lower frequencies than Fig. 1;

Fig. 5 shows an alternative construction for a part of Fig. 4; and

Fig. 6 shows another alternative construction for another part of Fig. 4.

Referring now to Fig. 1, a vessel or chamber 1 is provided of rugged pressure-resisting material such as steel. It is closed at one end by a pressure-responsive valve which may be a sheet of spring steel 2 fixed to one part of the vessel wall as at 3 and bearing, when closed, tightly and snugly against a valve seat 4, which may be continuous with the vessel wall, under the influence of its own elastic strains. In the figure the valve is shown by broken lines in the closed position and by full lines in the open position. The vessel is substantially closed at the opposite end by a light, rigid member such as an aluminum plate 5. The plate is not fixed to the inside walls of the vessel 1 but is free to move in the fashion of a piston at least over short distances. To the far side of the plate are fixed the ends of a considerable number of piezoelectric crystals 6, the other ends of which are similarly fixed to a massive, rigid backing block 7. The latter may be mounted on and supported by a skirt 8 movably engaging with a skirt 9, which may be an extension of the outer walls of the chamber 1. The assembly comprising the backing block 7, the crystals 6, the plate 5 and the skirt 8 may be moved bodily inward or outward of the chamber 1, correct positioning being effected as by turn buckles 10.

The piezoelectric crystal elements 6 may be cut from any suitable mother material, for example ammonium dihydrogen phosphate (ADP) to vibrate in their fundamental longitudinal mode. This material and the manner in which it should be cut are described and claimed in United States patent to Mason 2,450,010, September 28, 1948. The crystal lengths may be substantially one-quarter of the wavelength of a compression wave in the crystal material. Each one is provided on either side with a conducting plate or film 11, 11' which serves as an electrode in accordance with known principles of construction and operation. Corresponding electrodes 11 may be connected electrically in parallel and to one terminal of the primary winding of a transformer 12, the other terminal of which may be connected to the oppositely located crystal electrodes 11'. The secondary winding of the transformer 12 may be connected to supply a desired load 13 and, if direct current is desired, a rectifier 14 of conventional design may be interposed.

Because the crystals 6 may be injured by contact with water, it is desirable to surround them with oil which serves as a protection and also insulates the electrodes and the conductors from one another. Among other oils, castor oil is suitable for this purpose. To avoid the necessity of sealing the plate 5 to the inside walls of the chamber 1, the same oil 15 is supplied on both sides of the plate 5, hydrostatic pressures being equalized by leakage past the plate 5, that is, between the periphery of the plate 5 and the inner walls of the chamber 1. The oil extends to a diaphragm 16 which may be a simple sheet of rubber, or the like, which is sealed in any desired manner to the inner walls of the chamber 1 in leak-proof fashion. It may thus be easily deflected under the influence of unbalanced hydrostatic pressures without substantially modifying the operation of the apparatus while still serving to separate the oil 15 which lies to one side of it from the water which lies to the other side of it.

To the left (in the figure) of the diaphragm 16 stands a mass of water 17 which enters the chamber 1 from an intake pipe 18 by way of a manually adjustable cut-off valve 19 and a filter 20. The water mass 17 is retained in the vessel under static conditions by the force of the spring steel valve 2 but can escape by way of the opening between the valve 2 and its seat 4 when the valve 2 is deflected from the position shown in broken lines to the position shown in full lines.

The cross-section of the chamber 1 may be circular or rectangular or may have any other shape as desired. Its dimensions, which are related to the manner in which the apparatus operates, will be discussed hereinafter.

The length of the free-swinging portion of the spring valve 2 may be adjusted as by positioning a roller 21 against it in a desired location. The roller may be mounted on a bracket 22 arranged for movement in a direction parallel to the surface of the spring valve, being restrained against movements in any other direction as by guides 23. Its position may be manually adjusted as by a handwheel 24 and a threaded shaft 25 which engages with a nut 26 fixed to a projection from the vessel wall.

Further details of the structure of the apparatus will be better understood after the ensuing discussion of its operation.

In operation, the cut-off valve 19 is opened and water or other suitable fluid is admitted to the chamber 1 under pressure. The pressure may have any desired value but should not exceed two atmospheres, else injury to the apparatus by cavitation may occur. As the pressure is gradually increased up to the operating point, the hydrostatic pressure inside the chamber pushes outward against the spring steel valve 2, but the spring tension in the valve at first suffices to hold it in place against its seat 4. As the operating value of pressure is reached, the water pressure inside the vessel just balances the tension in the spring valve 2 and the valve opens slightly. Immediately water starts to escape through the narrow passage formed between the valve 2 and its seat 4. Due to the inertial characteristics of the water this flow does not start off instantaneously at its full value but accelerates gradually. Now it is well known that the pressure against the walls of a conduit through which a liquid is flowing rapidly is less than that which would obtain were the liquid at rest. This phenomenon is known as the "Bernoulli effect", after the name of the Swiss scientist who first investigated and analyzed it. Due to this effect the outward pressure on the valve 2 is less while the water is flowing through the passage than it is when the valve is closed. Therefore, the valve 2 having opened due to water pressure inside the vessel, the spring tension of the valve soon suffices to overcome the static pressure and the valve commences to close once more. As the valve closes, the passage through which the water escapes is more and more constricted. As the constriction of the valve proceeds, the speed of lineal flow through the passage increases while the volumetric flow of course decreases. Thus the pressure in the opening is more and more reduced as the valve closes until it is fully closed, whereupon the flow is arrested with a sudden jerk or hammer effect, the pressure rises very suddenly to its original value, and the full cycle is repeated.

Thus the spring valve 2 when properly adjusted, opens and closes periodically after the fashion of a vibrating reed, permitting the water to escape through the passage between it and the seat 4 in sharp spurts.

As above stated, closure of the valve 2 is accompanied by an increase in the pressure on its inner face while opening of the valve is accompanied by a reduction of such pressure. The cyclic recurrence of these increases and reductions in pressure at the surface of the valve are propagated away from the valve surface in the form of pressure waves. Each pressure wave travels axially of the vessel through the water 17, the diaphragm 16 which opposes only a negligible impedance to its passage, and through the oil 15 to impinge on the aluminum plate 5. The latter is a hard, rigid reflecting surface and it therefore reflects the wave without change of phase back again toward the valve 2. When the dimensions of the vessel are such that the reflected wave returns to the valve 2 at just the instant that the valve is closing so that a new pressure wave is starting from the valve 2, these waves become cumulative, and standing waves are formed in the vessel with nodes or high pressure regions at the valve 2 and at the aluminum plate 5. These pressure waves may contain substantial amounts of vibratory energy.

To obtain this standing wave condition it suffices that the time required for the full travel of one wave from the valve to the aluminum plate 5 and to return shall equal the period of vibration of the valve itself or an integral multiple thereof. This time depends principally on the propagation speed of sound in the propagating liquid, here mostly made up of water, which speed varies very little with variation in conditions such as temperature, pressure and the like. Therefore, in order to make the periods equal, applicant prefers to adjust the period of the valve. This may easily be accomplished in accordance with the invention by movement of the tuning roller 21 to adjust the length of the vibrating portion of the valve 2. This is analogous to the adjustment of the length of the beating reed of an instrument such as the clarinet by the lips of the player.

To preserve the pressure wave energy in the form of plane waves of the fundamental mode, in order to abstract as much as possible of this energy by vibration of the crystals 6, the diameter of the vessel 1, assuming its cross-section to be circular, or its shortest side, if rectangular, should not exceed one-half wavelength. This restriction is fully explained in "Electrical Transducers and Wave Filters" by W. P. Mason (Van Nostrand 1942).

In order further to prevent the escape of vibratory energy which does not affect the crystals, it suffices to provide a filter tuned to the frequency of vibration, in the intake line 18. A suitable and simple form of filter consists of a pair of oppositely arranged closed end branch pipes 20, each one-quarter wavelength long, measured from the axis of the intake pipe 18, and positioned one-quarter wavelength above the inner wall of the vessel 1, measured to the axes of the branch pipes. The theory, construction, and operation of such a filter, which permits free passage of a steady non-vibratory flow of water, is well known in the acoustic art and is fully explained in many publications, for example, "Elements of Acoustical Engineering" by H. F. Olson (Van Nostrand 1940).

Various types of valving arrangements may be employed in the apparatus. One less simple to construct than the spring 2 of Fig. 1, but which operates with even more suddenness and therefore with greater efficiency, is illustrated in Figs. 2 and 3. In this construction there are mounted on a rigid end plate 30 of the vessel 1 an array of inwardly projecting nozzles 31, each having a closed inward end but a central axial tubular passage which connects with a hole in one side wall. An elastic beating reed 32 is rigidly attached to the base of each of these nozzles 31. The reeds 32 are adjusted to stand slightly away from the side openings in the nozzles when the pressures on both sides of the reeds are alike. In operation, therefore, when water is first admitted to the vessel, it immediately starts flowing through the passages between the reeds and the nozzles. As it gathers speed, the pressure on the inward side of each reed is reduced in accordance with the Bernoulli effect, so that the reed tends to close the side opening. This still further increases the lineal velocity of the liquid and still further tends to close the opening. Finally the opening becomes tightly closed and the water flow is arrested with a sudden jerk or hammer effect, thus giving rise to an impulsive increase in pressure inside the vessel 1 in the neighborhood of the reed. The operation is therefore almost precisely like that of a clarinet, differing substantially only in the type of fluid medium. It should be recognized that Fig. 3 is diagrammatic to the extent that it does not show the reed which is related to each nozzle or the precise appearance of the nozzle as seen from the right, so as, for instance, to take account of the tapering conformation of the cross-section. It is thought that, in view of the number of the nozzles, a more detailed showing would be more confusing than instructive. This pressure increase travels axially of the vessel as described above, is reflected and returns to the plane of the plate 30 on which the reed valves are mounted, and operation continues as described in connection with Fig. 1.

It is characteristic of such a beating reed that it can vibrate with substantially equal effectiveness at any frequency within a relatively wide range. Therefore, the reeds 32 will attune themselves to and vibrate at the resonant frequency of the water oil-column 15, 17 in the chamber 1 without difficulty.

For best results, it is desirable that the natural frequency of vibration of each of the crystals 6 coincide with the natural period of vibration of the water-oil column 15, 17 in the chamber 1. To this end, the crystals should be initially cut to the proper length for operation at the desired frequency, and the dimensions of the vessel should be selected to match. Final adjustment can be made in any convenient manner but is preferably made by adjusting the length of the water-oil column in the vessel 1. To this end, the crystal array, with its mounting block, may be moved axially into and outward of the vessel as by adjustment of turn buckles 10. To prevent accumulation, positive or negative, of oil 15 under these circumstances, and consequent deflection or bulging of the diaphragm 16 in one direction or the other, oil may be added to or extracted from the oil chamber by way of the oil intake line and stop cock 34.

When the water in the vessel is in a state of standing wave vibrations at the lowest natural frequency, the middle regions of the vessel support the greatest water movement whereas the two ends support the greatest dynamic pressures. Therefore, the ends of the vessel are planes of high impedance. The high pressures bearing against the aluminum plate 5 actuate the crystals 6 and set them into longitudinal vibration. Because the crystals are each of a length equal to substantially one-quarter of the wavelength of the longitudinal vibrations of the crystal, the ends of the crystals 6 which are fixed to the aluminum plate 5 undergo the greatest movements while the other ends, fixed to the rigid backing plate 7, undergo substantially no movement. Thus, the outer ends of the crystals 6 lie in a plane of comparatively lower impedance than the backing plate ends. However, because the intrinsic impedance of the crystal as a medium is far in excess of the intrinsic impedance of water or oil as a medium, a good impedance match may be obtained between the high impedance end of the water-oil column 15, 17 and the low impedance ends of the crystals 6. The characteristic impedance of ADP crystal material is 600,000 mechanical ohms per square centimeter and the resonant impedance looking into the free ends of quarter wave crystals of this material is about one-fifth as great, or 120,000 mechanical ohms per square centimeter. The characteristic impedance of water or oil is about 150,000 mechanical ohms per square centimeter. Consequently, if the ends of the crystals 6 substantially fill the area of the plate 5, a good impedance match is obtained, and an efficient energy transfer will result.

The speed of sound in water or oil is about 4,400 feet per second. At a frequency of 10,000 cycles per second the full wavelength is only .44 feet or 5.2 inches, and the half wavelength only 2.6 inches. These small dimensions make for some awkwardness of construction and therefore it is recommended that at frequencies of the order of 2,000 cycles per second or more the apparatus be operated at one of its harmonics.

With a construction substantially equivalent to that illustrated in Fig. 1, an apparatus has been constructed which operates at a frequency of 10,000 cycles per second, with high efficiency, delivering one kilowatt of electric energy and drawing a flow of 36 cubic feet of water per minute under a static head of 15 pounds per square inch above atmospheric pressure. The vibrating water-oil column 15, 17 was one full wavelength, or 5.2 inches in length. The apparatus thus provides a very compact, as well as a simple, rugged and inexpensive source of electric energy.

The invention is not limited to such high frequencies or to the use of piezoelectric crystals as pressure responsive mechanical electrical transducers. Indeed, for lower frequencies, other types of transducers, for example, the electromagnetic type, are preferable. Fig. 4 shows a modification of the invention which is suitable for use at frequencies of the order of 60 to 200 cycles per second. Two resonant chambers or tubes 35, 35′ are provided which may be formed of standard steel piping, connected together and to a combination intake and discharge pipe 36 by way of a standard T-section coupling 37. Each tube is filled with water 38 and is one-half wavelength long, i. e., at a frequency of 200 cycles per second, 11 feet in length. The ends of the tubes are closed by metallic diaphragms 39, 39′ to the outer face of each of which is fixed a coil 40, 40′ of wire mounted and disposed to be moved by the diaphragm in the annular air-gap of a magnet 41, 41′. The magnets may, of course, be electromagnets if desired but the permanent magnets shown offer a certain convenience.

Valving action may conveniently be secured by a slide valve 42 which controls both intake and exhaust of the water 38. The slide valve may be arranged to be reciprocated by an eccentric 43 which may be driven by a synchronous motor 44. The pipe 36 may be divided by a septum 48 which separates the intake portion 46 from the discharge portion 47.

As it moves backward and forward, a port 49 which is cut through the slide 42 exposes the intake stand-pipe 46 and the discharge pipe 47 in alternation to the resonators 35, 35′. When the slide valve 42 is reciprocated at the proper resonant frequency of the resonators 35, 35′ the following sequence of operation takes place:

Assume that the port 49 suddenly opens the intake pipe 46. A small amount of water passes through the port and into the resonators 35, 35′. Acting against both the elasticity of the water 38 in the resonators and the elasticity of the diaphragms which terminate the resonators, this impulse sets up a compression condition. This condition of compression travels outward to the far ends of both resonator pipes 35, 35′, is there reflected by the diaphragms 39, 39′, and returned to the valve 42. Meantime the sleeve valve 42 will have reached the opposite position at which the intake passage 46 is closed and the discharge passage 47 is open. This permits some water to escape. At the same time, since the port 49 is small compared with the area of the junction pipe 36, a large portion of the energy of the returning wave is reflected back into the resonator pipes 35, 35′, for a second round trip. Thus to maintain a standing wave condition in each resonator pipe, it is only necessary to operate the slide valve 42 in such a way that the port 49 is opened to the intake 46 slightly after the low pressure point of the operation cycle and open to the discharge 47 one-half cycle later. Thus water is admitted at the instants when the hydrostatic pressure in the stand-pipe 46 outside the valve 42 exceeds the pressure in the resonator pipes 35, 35′.

The coils 40, 40′ may be connected in parallel by way of leads 50 to the primary winding of a transformer 51, of which the secondary winding supplies electrical energy to a load 52. If direct current is desired, a rectifier 53 may be interposed. A portion of the energy derived from the coils 40, 40′ may be fed back from the transformer 51, by way of an adjustable phase controlling device 54 to operate the synchronous motor 44, or to control the operation thereof, and so control the water input to the system.

If it be desired to make use of piezoelectric crystal elements at low frequencies in place of the electromagnetic devices of Fig. 4, this can be accomplished in various ways. For example, the resonator pipes may be terminated in composite piezoelectric elements of the type which respond to flexural distortion. Such elements are of many types, several of which are shown in Sawyer Patent 2,105,101. Fig. 5 shows one end of one of the resonator pipes 35 of Fig. 4, along the section X—X, modified in this way. Here the piezoelectric crystal assembly may consist of a pair of plates 55 of piezoelectric material such as Rochelle salt, ammonium dihydrogen phosphate (ADP) or the like, external electrodes 56, connected together and to one of the leads 50, and an internal electrode 57 connected to the other of the leads 50. The assembly may be held in place in any convenient manner, for example, between a shoulder 58 which may be integral with the pipe 35 or may be a threaded ring screwed into the pipe 35, and a screw cap 59. Diaphragms 60 of rubber or plastic may be employed to protect the crystals 55 from the water 38, and to prevent short-circuiting of the electrode 56 by the cap 59.

The remainder of the apparatus may be similar in all respects to the apparatus of Fig. 4 and may operate in the same way.

Another way in which piezoelectric elements may be employed is indicated in Fig. 6, which shows a construction alternative to the portion of Fig. 4 lying to the right of the section Y—Y, it being assumed that the structure to the left thereof duplicates this structure. Here the pipes 35 are closed at their ends as by inactive reflecting pipe caps 61, while a multitude of piezoelectric crystal elements 62, each provided with a pair of electrodes 63, 64 are distributed throughout the volume of the resonator pipes 35. To avoid injury to the crystals by water, it is preferable to use a suitable chemically inactive oil 65 as the wave supporting medium. To avoid the necessity of supplying oil as the ultimate power source, the oil may be confined in the resonator pipes as by diaphragms 66 of some material such as artificial rubber which is not injured either by water or oil. The crystals 62 may be of a material such as lithium sulphate (Li—SO_4—H_2O).

Operation takes place in the manner described above in connection with Fig. 4. The rubber diaphragms 66 offer only a negligible impedance to the passage of the wave energy, being deflected outward and inward alternately as the water is injected by way of the intake pipe 46 and discharged by way of the exhaust pipe 47. The compression wave travels through the oil and among the crystals to the ends of the pipes 35 where it is reflected by the end caps, and returns. As in the case of the apparatus of Fig. 4, a standing compression wave of considerable amplitude is thus set up in the resonator pipes and each of the piezoelectric crystals is subjected to the pressures of this wave and responds by the appearance of an electric charge on its electrodes. Corresponding electrodes may all be connected in parallel, and the electric charges may be withdrawn as an electric current and be supplied by way of the transformer 51 to the load 52. As with the apparatus of Fig. 4, a portion of the energy so derived may be fed back to the synchronous motor 44 to control the timing of the valve 42.

Various modifications of the arrangements shown will suggest themselves to those skilled in the art as being within the spirit of the invention whose scope is defined in the appended claims.

What is claimed is:

1. A source of oscillatory energy which comprises a closed vessel, a fluid within said vessel capable of supporting standing waves of a given natural frequency and wavelength determined by the dimensions of the vessel, a port for admitting fluid under pressure into said vessel, a flexible, reed-like valve member adapted, as in accordance with the Bernoulli effect, to open and close a passage in alternation under influence of pressures within said vessel and the flow of said fluid through said passage, a baffle element in said vessel and fluid, a mechanical-electrical transducer element coupled to said fluid through said baffle element, and means to positionally adjust a boundary of said vessel, said baffle element, and said transducer element as a unit to tune the vessel and contents to said frequency, said transducer element also being dimensioned to be tuned to said frequency.

2. A source of oscillatory energy which comprises a closed vessel, a flexible partition dividing said vessel into at least two compartments, a first fluid within one compartment capable of supporting standing waves of a given natural frequency and wavelength determined by the dimensions of the vessel said vessel being so dimensioned as to accord with said given frequency, a supply of a second, and different, fluid, a water hammer type of means for periodically admitting said second fluid to another compartment and discharging said fluid from said second compartment to develop standing waves in said first fluid, a baffle element in said first fluid, and a plurality of hydrostatic pressure-responsive piezo electric elements positioned in said first compartment and coupled to said first fluid through said baffle element.

3. A source of oscillatory energy which comprises a closed vessel, a flexible partition dividing said vessel into at least two compartments and opposing a negligible impedance to the passage of compression wave energy therethrough, a first fluid in one compartment, a second, and different, fluid in another compartment, a supply of said second fluid, a tunable resonantly vibratable valve for periodically admitting fluid from said supply to said second compartment and discharging said second fluid from said second compartment, to develop standing compression waves in said two fluids, a baffle element in said first fluid, and a plurality of hydrostatic pressure-responsive piezoelectric elements positioned in said first compartment and coupled to said first fluid through said baffle element.

4. A source of oscillatory energy which comprises a closed vessel, a flexible partition dividing said vessel into at least two compartments and opposing a negligible impedance to the passage of compression wave energy therethrough, a first fluid in one compartment, a second, and different, fluid in another compartment, a supply of said second fluid, a valve for periodically admitting fluid from said supply to said second compartment and discharging said second fluid from said second compartment, to develop, as in accordance with the water hammer principle, standing compressional waves in said two fluids, a pressure-responsive mechanical-electrical transducer element coupled to said first fluid by attachment to said first compartment, and means to positionally adjust a boundary element of said vessel and said transducer element as a unit to tune the vessel and contents to the frequency of said compressional wave, said transducer element also being dimensioned to be tuned to said frequency.

WARREN P. MASON.

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