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Bernstein et al.

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[54] UNIPOLAR ACOUSTIC PULSE GENERATOR

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[52] **U.S. Cl.** .....**340/5 R,** 340/15

[51] **Int. Cl.** **H04b 11/00**

[58] **Field of Search**.....340/3 A, 5 R, 3 R, 15; 181/0.5 A, 0.5 R

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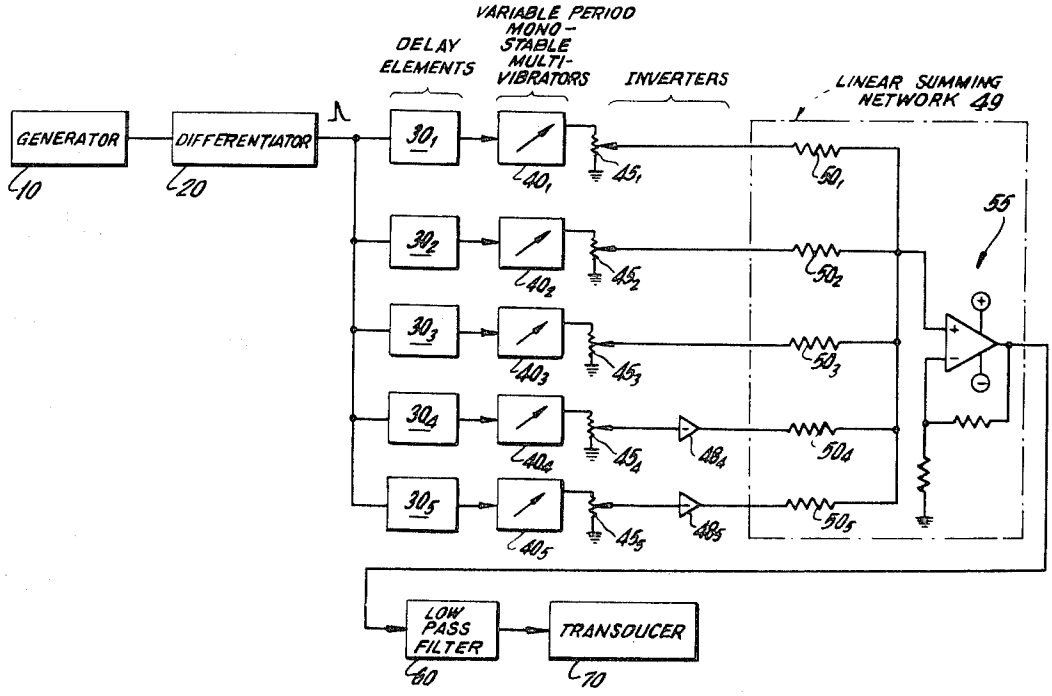
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[57] **ABSTRACT**

Unipolar acoustic pulses of relatively large amplitude and short duration are formed by driving an electroacoustical transducer with a generally staircase-shaped waveform, advantageously through a low pass filter. The applied waveform is formed by linearly summing constituent electrical pulses of preselected amplitude, duration, polarity, and relative time of occurrence. The transducer driving signal acts to reinforce the transducer output in the desired direction, while opposing its output in the reverse direction.

22 Claims, 12 Drawing Figures



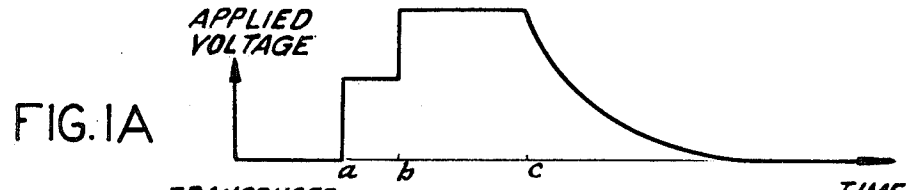


FIG. 1A

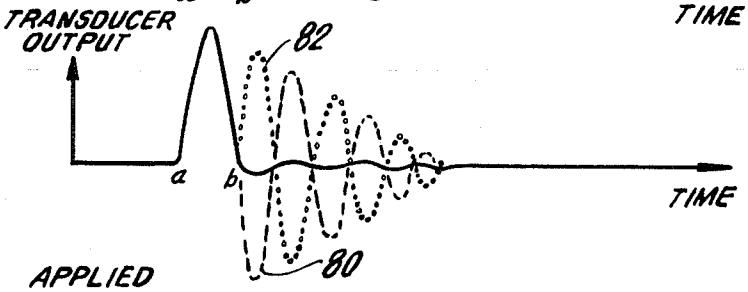


FIG. 1B

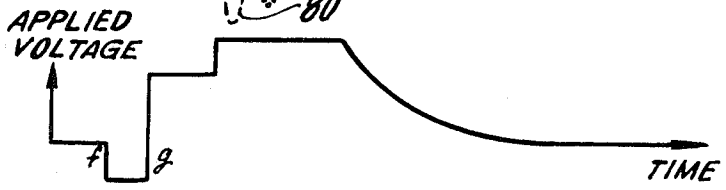


FIG. 1C

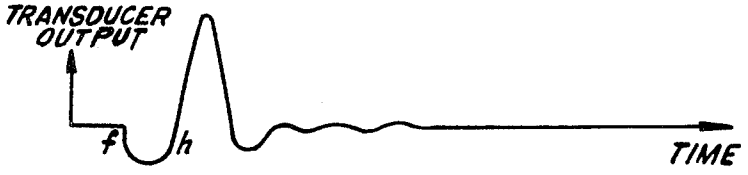


FIG. 1D

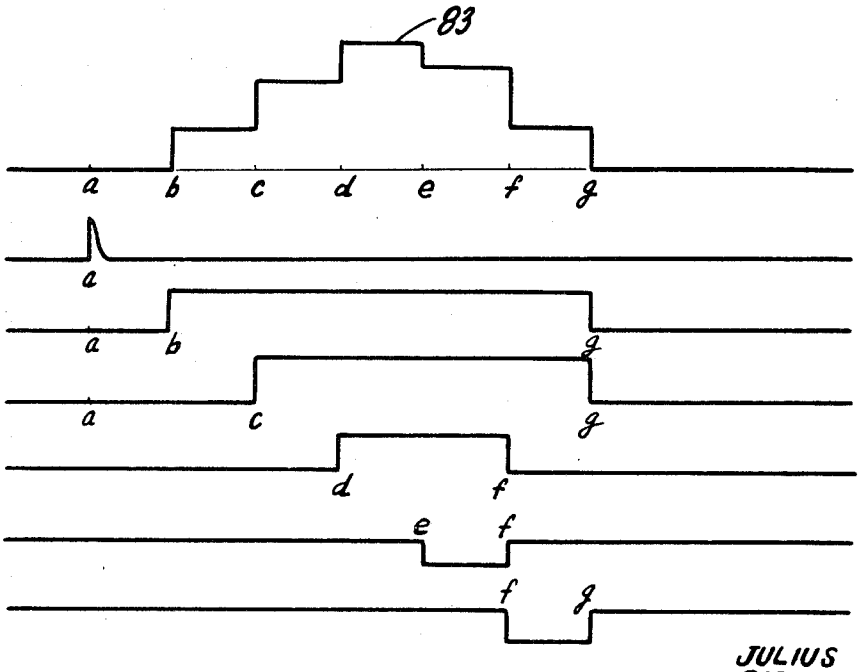


FIG. 2A

FIG. 2B

FIG. 2C

FIG. 2D

FIG. 2E

FIG. 2F

FIG. 2G

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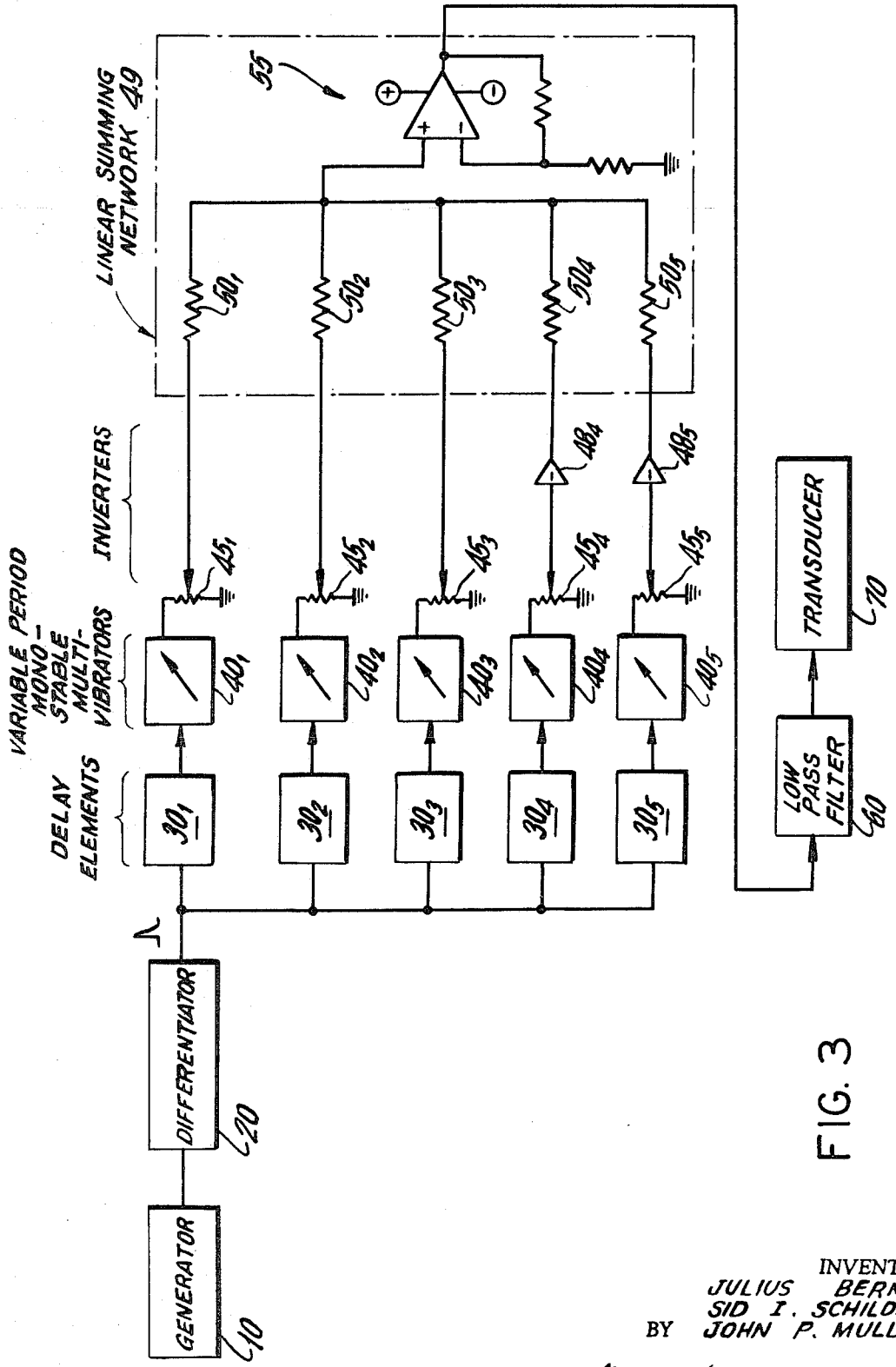


FIG. 3

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UNIPOLAR ACOUSTIC PULSE GENERATOR

This invention relates to transducer apparatus and, more specifically, to a system for producing high energy unipolar pulses in an environmental medium.

Transducers for radiating energy in a medium, e.g., electroacoustic projectors for an underwater environment, are well known. Such transducers are typically supplied with a continuous or pulsed alternating current driving wave of either a single frequency, or a band of frequencies. The transducer converts the driving electrical wave into corresponding alternating acoustic pressure perturbations in the water for propagation away from the transducer, The radiated acoustic wave may be employed, for example, for navigation, survey, docking, underwater object detection, and communication applications, among others.

However, for some purposes, large amplitude, unipolar acoustic pulses are preferred. Such pulses have a relatively long range and depth penetration capability by reason of their amplitude, and the relatively sharp pulse edges give rise to information of relatively fine resolution useful, for example, in an underwater survey or object detection and discrimination application. Reverberation signals, directly related to pulse length, may be reduced by employing pulses which may be made as short as desired.

One limiting factor for the peak energy which can be radiated by the transducer is that of water cavitation. Transducers by their inherent nature are bipolar devices, and include a water displacing vibratory member which is alternately displaced on both sides of central rest position. When a transducer is driven toward a large extended displacement, the ambient fluid in proximity to the transducer vibratory member cannot follow the member as it translates toward a correspondingly large reverse displacement, thus resulting in void areas adjacent the transducer face. These void areas aerate the water, thereby limiting the acoustic transmission propagation and producing electrical noise in electronic signal processing equipment associated with the transducer.

To avoid or reduce water cavitation related difficulties, unipolar acoustic waves have been employed. Since transducers have classically been viewed as alternating current, or bipolar devices, the large amplitude, unipolar pulses have been produced by underwater explosion, mechanical impact, or hydromechanical or electromechanical apparatus. It is obviously highly desirable to develop these pulses electroacoustically under electronic control, but appropriate apparatus for accomplishing this has not heretofore been available.

It is thus an object to provide improved acoustical pulse generating apparatus.

More specifically, an object of the present invention is the provision of apparatus for electroacoustically producing essentially unipolar pulses of relatively large amplitude.

The above and other objects of the present invention are realized in a specific, illustrative transducer driving arrangement wherein a staircase-shaped waveform is applied to an acoustic transducer, e.g., formed of cylindrical piezoelectric member with or without front and rear mass loadings, advantageously via a low pass filter. The input waveform may be formed by linearly summing a plurality of time-spaced pulses of selected amplitude, duration, relative time of occurrence, and polarity.

The applied waveform stimulates and reinforces movement of a transducer vibratory member in the desired direction. Further, the driving signal opposes the natural propensity of the movable transducer member to be displaced in the undesired direction in accordance with the several natural vibratory modes of the device. Accordingly, the transducer produces a large acoustic output wave in the water of essentially only a single polarity, i.e., wherein the acoustical output wave is much larger in the desired direction than in the reverse direction.

In accordance with one feature of our invention, the transducer may be initially energized for a small translation in the reverse direction, and then stimulated when it reverses direction toward the desired output polarity.

The above and other objects, features and advantages of the present invention are realized in a specific illustrative embodiment thereof, discussed hereinbelow in conjunction with the accompanying drawing, in which:

FIGS. 1A–1D are waveforms illustrating the underlying principles of the present invention;

FIG. 2A depicts a specific, illustrative waveform for driving an electroacoustical transducer for producing a unipolar output waveform; form;

FIGS. 2B–2G comprise a set of signals for forming the waveform of FIG. 2A; and

FIG. 3 is a block diagram of an electronic system for generating the waveform of FIG. 2A.

As discussed above, it is desirable for selected underwater acoustical energy radiating applications that unipolar output pulses of relatively large amplitude be employed. The large amplitude of such pulses provides range and depth penetrating capabilities; the unipolar nature of each such pulse permits larger amplitude pulses while maintaining cavitation within acceptable levels; and the narrow pulse width with the concomitant quickly rising and falling pulse edges provides detailed information resolution largely free from reverberation problems.

Transducers for underwater applications, i.e., projectors, are of several constructions well known to those skilled in the art. For example, one such transducer is formed of an array of hollow cylindrical piezoelectric ceramic elements, e.g., formed of barium titanate or lead zirconate. Metallic masses are attached to the ends of the piezoelectric cylinder, with the cylindrical segments being electrically interconnected for receiving transducer driving electrical energy. The above-described transducer, in common with other transducer configurations, is inherently a bipolar, or alternating current device. That is, the active (piezoelectric) material has a normal rest position, and mechanically departs from the rest position when excited. For the above-considered transducer, the piezoelectric material axially elongates and contracts when excited, thereby cyclically moving the front mass axially through the water to produce the desired acoustical wave. After undergoing a displacement in a first direction, the active transducer material and the connected water urging mass pass through their rest position and then become disposed in the alternate direction, thereby providing a bipolar output acoustic wave. This bipolar acoustic output occurs even if the driving signal applied to the transducer is of only one

polarity. When excited with a large applied unipolar signal to drive the water urging mass to a large peak displacement, water cavitation problems are thus produced as the movable vibratory mass moves toward a comparable displacement on the other side of its quiescent or rest position with a frequency corresponding to one or more of the several natural or resonant frequencies for the transducer.

Our basic invention for driving an electroacoustical projector to produce a unipolar output may be understood from the waveforms shown in FIGS. 1A–1D. Referring first to FIGS. 1A–1B, FIG. 1A depicts a particular transducer driving waveform, and FIG. 1B illustrates the response to the waveform of FIG. 1A for an ideal transducer having a single natural vibratory mode. At a time *a* of FIG. 1A, a step function is applied to the transducer such that the output of the transducer increases in the desired positive acoustic output direction, as shown following the time *a* in FIG. 1B. The transducer output, i.e., the intensity of the acoustic output produced by the vibratory transducer member, becomes increasingly positive, attains a peak amplitude, and returns to zero at the natural transducer frequency. Corresponding times are shown vertically aligned in FIG. 1A and 1B and elsewhere in the drawing for clarity of presentation. It must be appreciated, however, that there is in fact a delay between the application of signals to the transducer, and the response of the transducer to the applied signal.

Absent any further applied signal, the moving transducer mass would continue through zero output displacement following a dashed path **80** and proceed with time to define a damped output oscillation. However, at a time *b* substantially corresponding to the zero crossing of the transducer response of FIG. 1B, we apply a further positive voltage step to the transducer. Were the transducer inert at the time *b*, the transducer output would follow the dotted path **82** to define the damped oscillatory time function shown in FIG. 1B. However, for the actual case, the natural tendency for the transducer to go negative following the time *b* is directly opposed by the applied additional driving step at the time *b* such that the waveforms **80** and **82** essentially cancel. Thus, following time *b*, the actual output of the transducer is maintained within narrow bounds about zero output producing neither negative nor positive significant acoustic perturbations.

Some time following the time *b* when the transducer is largely passive, e.g., following the time *c* of FIG. 1A, the applied driving voltage is restored to zero without shock exciting the transducer, such that subsequent pulses may be developed, if desired, at an appropriate repetition rate from a like initial level.

The first positive pulse of the transducer output of FIG. 1B is much larger in amplitude than any subsequent positive or negative excursion, thereby producing the desired unipolar pulse. Moreover, the pulse rises and falls in short order, with the interval a-b being as small as desired. In one application of the two step waveform of the FIG. 1A type applied to a transducer formed of eight lead zirconate elements connected in parallel, a pulse was generated with a four-to-one maximum positive-to-negative excursion ratio.

In accordance with another feature of the present invention, the transducer may initially be excited in the reverse direction at a relatively low level, as shown in FIGS. 1C and 1D for the applied impulse following the time f. This overcomes inertia and starts the transducer element moving. Sometime following the peak negative excursion in the interval *f–h* when the transducer mass is moving in the desired output direction, e.g., at the time *g*, the waveform of FIG. 1A is applied to the transducer to drive it in the positive direction, and to suppress subsequent oscillatory motion as discussed above. The peak amplitude of the output pulse produced by the applied signal of FIG. 1C is somewhat larger than that for a comparable driving signal for the wave of FIG. 1A since the vibratory transducer member is already moving in the proper direction when the initially positive energy step excites the device.

It is observed that the driving waves of FIGS. 1A and 1C have been shown as formed of flat-topped steps. However, since the desired transducer response is largely dictated by the transitional portions of the applied wave, the flat wave segments may exhibit drooping or rising characteristics which are slow relative to the transducer response and to the transitional properties of the applied wave.

In contrast to the ideal transducer assumed for the waveforms of FIGS. 1A–1D, existing electroacoustical transducers exhibit more than one natural moment of oscillation. For example, for the above-considered transducer construction, the piezoelectric material is characterized by one or more vibratory modes in each physical direction, i.e., about its length, circumference, and thickness. Thus, the response of a transducer to an applied step function is not strictly a damped sinusoid, but is a more complex damped bipolar function consisting of combinations of the several resonant modes. Accordingly, the staircase-shaped waveform applied to any specific transducer may be more complex than that of FIGS. 1A or 1B, e.g., of the form shown by the waveform **83** of FIG. 2A, which consists of several steps of varying width, amplitude, and relative time of occurrence. In overall terms, the staircase waveform includes level transitions to produce and reinforce the positive going displacement of the transducer moving element, and to apply a driving impetus to the transducer to cancel transducer displacements subsequent to the desired unipolar pulse which would otherwise obtain.

Particular apparatus for generating the transducer driving waveform of FIG. 2A is shown in block diagram form in FIG. 3. In overall terms, the structure of FIG. 3 develops the staircase type waveform by generating individual rectangular shaped pulses of adjustable polarity, amplitude, and relative time of occurrence. These individual rectangular pulses are then linearly summed to develop the composite signal. For example, it is apparent that the set of waveforms of FIGS. 2C–2G comprise one non-unique set of signals which, when linearly added, will generate the complex function of FIG. 2A.

The structure of FIG. 3 includes a generator **10** and differentiator **20** for generating an output trigger pulse, such as that following time *a* of FIG. 2B, at the desired repetition rate for the transducer output pulses. Each trigger pulse is connected to a plurality of rectangular pulse developing channels, these being five in number to develop the signals of FIGS. 2C–2G to form the particular desired pulse of FIG. 2A. Each channel includes

a delay element, e.g., a monostable multivibrator, for defining the timing of the leading edge of the rectangular pulse produced by that channel relative to the trigger pulse, Thus, the delay 30_1 in the upper channel which develops the waveform of FIG. 2C produces a delay corresponding to the interval *a—b* (this delay element 30_1 may be deleted if the output wave is to begin concurrent with the trigger pulse); the delay 30_2 produces a delay equivalent to the period *a—c*, the second channel producing the pulse of FIG. 2D; and so forth.

The delayed trigger in each channel is coupled to a timed pulse generating circuit, e.g., a monostable multivibrator exhibiting an output pulse period dependent upon the values of circuit elements in the manner long known. The multivibrator 40_1 produces an output pulse of width *b—g* (see FIG. 2C), the unit 40_2 produces a pulse of width *c—g*, and so forth through the fifth channel which produces an output pulse of duration *f—g*. The output pulse produced by each multivibrator 40_i is adjusted to the appropriate amplitude, as by an associated potentiometer 45_i and the supplied to a linear summing network either directly, or via an inverting amplifier **48** where a negative pulse is required. The linear summing network may comprise an array of resistors **50** having a common output node, and a following operational amplifier **55** may be used for buffering and drive pulse amplitude implementation and adjustment. The resistors **50** may be of the same value where the relative amplitudes of the several constituent pulses are adjusted by potentiometers **45**. Alternatively, the resistors may be of weighted values of vary the relative amplitude of the several input rectangular pulses, and the potentiometers **45** eliminated.

Thus, the output of the linear summing network **49** directly comprises the desired waveform of FIG. 2A which may be directly applied to drive a transducer **70** to produce the desired unipolar output pulse as described above.

In accordance with one aspect of our invention, we have found that improved transducer performance results when the driving staircase waveform, such as that of FIG. 2A, is passed through a low pass filter **60** before being applied to the transducer **70**. The filter may, of course, be included as part of the linear summing network in any well known manner to provide a frequency attenuating characteristic beginning at a relatively low frequency. The use of such a low pass filter has been found to improve the overall transducer output waveform by suppressing undesirable cross-resonances and the like which occur in three dimensional devices.

Thus, the apparatus of FIG. 3 has been shown by the above to develop waveforms of the type shown in FIGS. 1A, 1C, and 2A to produce an essentially unipolar output acoustic wave under electronic control which may be employed for the purposes discussed above.

It is to be understood that the above-described arrangement is merely illustrative of the principles of the present invention. Numerous modifications and adaptations thereof will be readily apparent to those skilled in the art without departing from the spirit and scope of the present invention.

What is claimed is:

1. Apparatus for generating a unipolar acoustic wave of a given polarity comprising:

a transducer;

means for generating a discontinuous signal having a sudden transition in amplitude timed to coincide with a first zero output transition in the characteristic response of said transducer to an initial signal discontinuity for substantially dampening the response of said transducer, and at least one further sudden transition in amplitude timed to coincide with a zero output transition in the dampened transducer response for further dampening said transducer response, said sudden transitions in signal amplitude acting to suppress the transducer acoustic output of undesired polarity; and

means for applying said discontinuous signal to said transducer.

2. The apparatus defined in claim **1** wherein said means for generating a discontinuous signal comprises:

means for generating a plurality of substantially stepped output signals; and

means for additively combining said stepped output signals to produce said discontinuous signal.

3. The apparatus defined in claim **2** wherein said means for applying said discontinuous signal to said transducer includes means for low pass filtering said discontinuous signal.

4. The apparatus defined in claim **2** wherein said means for generating a plurality of substantially stepped output signals comprises means for timing the start of at least one of said stepped output signals to coincide with said first zero output transition in the characteristic response of said transducer.

5. The apparatus defined in claim **4** wherein said means for generating a plurality of substantially stepped output signals further comprises means for timing the start of at least one further stepped output signal to coincide with said zero output transition in said dampened transducer response.

6. The apparatus defined in claim **2** wherein said means for generating a plurality of substantially stepped output signals comprises:

trigger signal generating means;

a plurality of delay means responsive to said trigger signal generating means for producing a plurality of delayed trigger signals; and

a plurality of monostable multivibrators, each responding to one of said delayed trigger signals by starting to generate a stepped output signal of predetermined duration.

7. The apparatus defined in claim **6** wherein said means for applying said discontinuous signal to said transducer includes means for low pass filtering said discontinuous signal.

8. The apparatus defined in claim **6** wherein the start of at least one of said stepped output signals is delayed relative to said initial discontinuity to coincide with said first zero output transition in the characteristic response of said transducer.

9. The apparatus defined in claim **8** wherein the start of at least one further stepped output signal is delayed relative to said initial discontinuity to coincide with said zero output transition in said dampened transducer response.

10. The apparatus defined in claim **1** further comprising means for initially exciting said transducer for movement in a direction opposite to that of said unipolar acoustic wave.

11. Apparatus for generating a unipolar acoustic wave comprising:

a transducer having a plurality of resonant modes of oscillation;

means for generating a discontinuous signal having a sudden transition in amplitude timed to coincide with a first zero output transition associated with oscillation of said transducer in a predetermined one of said resonant modes in response to an initial signal discontinuity for substantially dampening the oscillation of said transducer in said predetermined mode, and at least one further sudden transition in amplitude for substantially dampening the oscillation of said transducer in a mode other than said predetermined mode; and

means for applying said discontinuous signal to said transducer.

12. The apparatus defined in claim 11 wherein said means for generating a discontinuous signal comprises means for timing said further signal sudden transition to coincide with a further zero output transition in the response of said transducer.

13. The apparatus defined in claim 12 wherein said means for applying said discontinuous signal to said transducer includes means for low pass filtering said discontinuous signal.

14. The apparatus defined in claim 11 wherein said means for generating a discontinuous signal comprises:

means for generating a plurality of stepped output signals and

means for additively combining said stepped output signals to produce said discontinuous signal.

15. The apparatus defined in claim 14 wherein said means for generating a plurality of stepped output signals comprises means for timing the start of at least one of said stepped output signals to coincide with said first zero output transition.

16. The apparatus defined in claim 15 wherein said means for generating a plurality of stepped output signals further comprises means for timing the start of at least one further stepped output signal to coincide with a further zero output transition in the response of said transducer.

17. The apparatus defined in claim 16 wherein said means for applying said discontinuous signal to said transducer includes means for low pass filtering said discontinuous signal.

18. The apparatus defined in claim 14 wherein said means for generating a plurality of stepped output signals comprises:

trigger signal generating means;

a plurality of delay means responsive to said trigger signal generating means for producing a plurality of delayed trigger signals; and

a plurality of monostable multivibrators, each responding to one of said delayed trigger signals by starting to generate a stepped output signal of predetermined duration.

19. The apparatus defined in claim 18 wherein the delay means associated with at least one of said monostable multivibrators delays the triggering of said monostable multivibrator relative to the triggering of a first of said monostable multivibrators to correspond to said first zero output transition.

20. The apparatus defined in claim 19 wherein the delay means associated with at least one further monostable multivibrator delays the triggering of said further monostable multivibrator relative to the triggering of said first monostable multivibrator to correspond to a further zero output transition in the response to said transducer.

21. The apparatus defined in claim 20 wherein said means for applying said discontinuous signal to said transducer includes means for low pass filtering said discontinuous signal.

22. The apparatus defined in claim 11 further comprising means for initially exciting said transducer for movement in a direction opposite to that of said unipolar acoustic wave.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,715,710 Dated February 6, 1973

Inventor(s) Julius Bernstein; Sid I. Schildkraut and John P. Muller

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Cover page, before "Filed: Nov. 25, 1970", insert,

commencing a new paragraph:

--Assignee: Edo Corporation, College Point, New York--

Signed and sealed this 11th day of June 1974.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents

PO-1050
(5/69)

UNITED STATES PATENT OFFICE
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