

Aug. 3, 1965

D. A. BUNGER

3,199,053

TAPERED SPRING REVERBERATION DELAY LINE

Filed Sept. 18, 1964

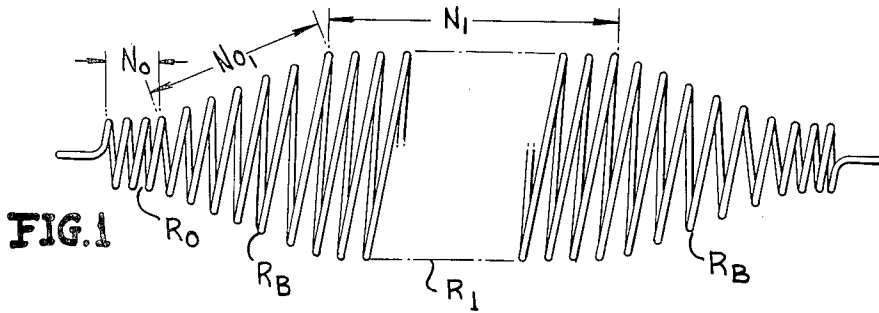
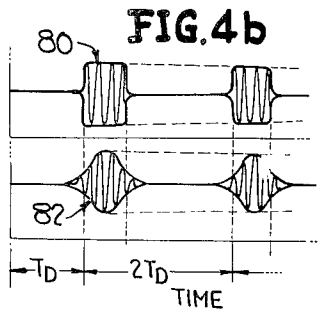
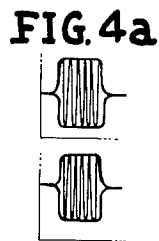
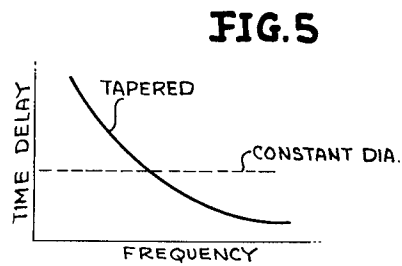
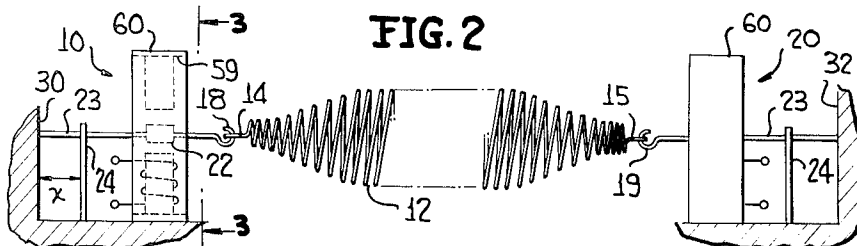
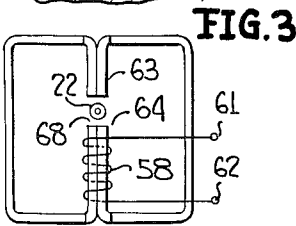
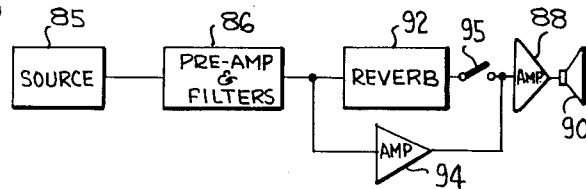
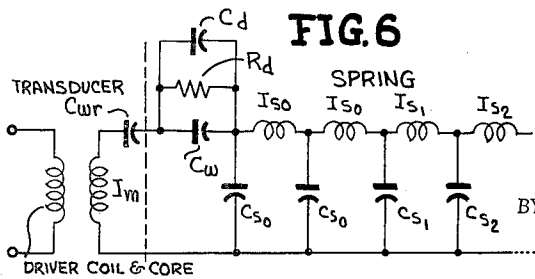


FIG. 7

INVENTOR
DAVID A. BUNGER

William H. Breunig, Agent

BY *Hurnitz & Rose*

ATTORNEYS

1

2

3,199,053
TAPERED SPRING REVERBERATION
DELAY LINE

David A. Bunker, Cincinnati, Ohio, assignor to D. H. Baldwin Company, Cincinnati, Ohio, a corporation of Ohio

Filed Sept. 18, 1964, Ser. No. 397,482
17 Claims. (Cl. 333—30)

The present invention relates generally to reverberators and, more particularly, to electromechanical reverberation apparatus capable of simulating reverberation properties of large reverberant enclosures.

One of the problems involved in providing a sound reproduction system of high quality is that of artificially recreating the reverberative responses of a large room. That is, it is more desirable that the system give the listener the impression that the sound, and more particularly music emanating from the system, has the reverberant quality which typifies music presented in a concert hall, opera house, or the like. In a concert hall environment, "live" musical sounds are reflected from surface to surface of the hall, being only partially absorbed at each, to produce a gradual decay of the sound in accordance with a predetermined transient behavior and reverberation time. The effect of these multiple reflections is an enhancement of the music, which is pleasant to many members of the listening audience. On the other hand, if the same initial sounds are instead generated in a small room having highly sound-reflective walls, i.e., acoustically hard surfaces, the resulting reflections would produce a rather unpleasant series of harsh or abrupt periodic repetitions of the sound, an effect which is characterized as flutter. The effects are due largely to room diffusion characteristics and reverberation time of the environments.

In electroacoustical systems, simulated sound reverberation has generally been accomplished by the use of one or more helical springs acting as mechanical delay lines at audio frequencies. Typically, such a delay line might comprise a constant diameter helical spring driven by a driver transducer in a particular mode, to generate mechanical vibrations thereon traveling along the spring. The vibrations are subsequently detected by one or more pickup transducers located at one or more selected points of the line. In this manner, electrical signals representative of selected sounds, are converted to mechanical vibrations and are subsequently reconverted to electrical signals. The spring, of course, causes a delay by virtue of the relatively slow travel of the mechanical vibrations thereon. In addition, the structural characteristics of the line and its terminations are arranged to produce multiple reflections from upon the termination points.

The torsional mode of propagation of such vibrations is preferred, because, in general, the spring is subjected to practically no undesired perturbations occurring in that mode at the frequencies of interest. However, torsional vibrations transmitted along the constant diameter spring propagate at substantially uniform velocities irrespective of frequency, at least in the audio frequency range of interest where the wavelengths include at least four turns of the helix. A pulse of complex waveform consisting of a multitude of frequencies, i.e. the fundamental and harmonics thereof, will therefore travel along the spring with a constant velocity for all its frequencies and each reflection will consequently occur simultaneously for all frequencies. The result is a series of abrupt periodic reflections, each constituting, in form, a pulse-like envelope containing a complex waveform, the pulses being spaced at intervals proportional to the time delay per unit length of the spring. The electroacoustical system output will contain these abrupt periodic reflections as audible sounds of a type analogous to the previously described

sonic repetitions occurring in a room having acoustically hard surfaces. Similarly, this system response is characterized as involving severe flutter.

In an effort to overcome flutter in sound reproduction systems, it has been the practice to employ a plurality of springs, each having a different delay time, and thus, in combination, providing artificial reverberation of less abrupt nature. However, while multi-spring reverberation apparatus has been effective to some extent in reducing flutter, it will be apparent that such apparatus has several distinct disadvantages. The cost of the reverberation apparatus is proportional to the number of springs and transducers required; increased production time is necessary for the construction and incorporation of the reverberation apparatus into the system over that which would be required in the case of a single spring; there is an increased sensitivity to cabinet attitude; and there is an increase in the amount of space required to house the apparatus. In addition, it is to be recognized that when several springs of different delay times are used, there is, of course, no change in the abrupt reflection characteristics of each spring, but simply an appearance of smoother transition in the reflections by virtue of the combined action of all the springs. Thus, in the event that one of the springs and/or the transducers associated therewith should become inoperative, for one reason or another, system flutter would increase. Further, an increase in the number of elements employed ultimately results in an increase in the number of sources of possible failure trouble in the system.

It is, accordingly, a principal object of the present invention to overcome one or more of the above-mentioned disadvantages associated with prior art reverberation apparatus for electroacoustical systems.

Briefly, and in accordance with the present invention, a single helical spring is employed as a mechanical delay line in an audio reverberation system, the spring having a linearly tapering helix diameter over portions of its length, which produces a significant variation in the delay time of vibrational waves transmitted thereby as a function of wave frequency. Vibrational wave motion is initiated in the spring in a non-dispersive, i.e., frequency insensitive, mode of propagation, is translated to a dispersive, i.e., frequency sensitive, mode at a predetermined helix radius along an increasing taper, and is subsequently converted back to a non-dispersive mode at a corresponding radius along a decreasing taper, the helix radius at which each mode transition occurs being a function of wave frequency. In other words, the effective length of the spring, viewed from the position of waves transmitted therein, varies for each frequency component of the wave motion by virtue of the dependence of the mode transition radius on wave frequency. By incorporating impedance discontinuities at the termination points of the line the waves are partially reflected in a repetitive fashion, undergoing the above-described transitions during each trip.

The advantages of such a tapered spring delay line are immediately apparent. Since each frequency component of the complex wave is delayed by a different time interval, the problem of flutter is overcome in an extremely simple and inexpensive manner. The output of the sound system contains some diffused reverberation which is characteristic of acoustically well designed auditoriums. Moreover, the use of a tapered spring delay line permits the system designer to readily adjust the delay time versus frequency characteristic of the reverberator to fit substantially any desired curve, subject to practical restrictions imposed on physical dimensions, by simply varying the rate of taper, or by variation of other parameters, as will hereinafter be discussed. Additional advantages deriving from the present invention

are the compactness and simplicity of a single spring reverberator and the reliability of operation thus accruing from a reduction in reverberator components.

It is accordingly a further object of the present invention to provide a mechanical delay line including a tapered helical spring wherein effective or acoustic spring length varies as a function of wave frequency.

Another object of the present invention is to provide electromechanical reverberation apparatus including a single spring delay line which may readily be tailored to provide desired delay time versus vibrational wave frequency characteristics.

Other objects, features, and attendant advantages of the present invention will become apparent from a consideration of the following description of a particular embodiment thereof, especially when taken in conjunction with the following drawings in which:

FIGURE 1 is an elevational view of a tapered spring in accordance with the present invention;

FIGURE 2 is a side elevational view illustrating one end of a tapered helical spring connected to a portion of the transducer apparatus and to a support;

FIGURE 3 is a diagrammatic view of a portion of a preferred transducer;

FIGURE 4a is a graph illustrating two similar pulses of audio frequency torsional vibrations respectively applied to a single, constant-diameter spring reverberator and to a single, tapered spring reverberator;

FIGURE 4b is a graph illustrating the difference in reflection envelopes in a single constant diameter spring reverberator and in a single tapered spring reverberator;

FIGURE 5 is a graph of time delay versus frequency for tapered spring delay line and for constant diameter spring delay line;

FIGURE 6 is a schematic diagram illustrating the equivalent electrical circuit for a portion of the reverberator of FIGURE 2; and

FIGURE 7 is a block diagram of one type of electroacoustical system in which the tapered spring reverberator may be utilized.

Referring now to FIGURE 1, there is illustrated a tapered helical spring, accompanied by symbolic designations which will be of aid in following the subsequent discussion of wave transmission properties. The spring preferably comprises a helically wound coil of, for example, 8 to 15 mil diameter beryllium copper wire, or music wire. At either end thereof the helix radius is R_0 which is maintained constant for a number of turns N_0 , after which the radius varies, in a uniformly tapering fashion in this case, over a number of turns N_{01} to a larger radius R_1 . Radius R_1 is constant for a centrally located number of turns N_1 . The radii R_0 and R_1 will hereinafter be designated the minimum and maximum radii, respectively, of the helix, but it is also to be understood that this will refer to relative dimensions and not to limitations or restrictions on such dimensions. Further, in the limit, N_0 and N_1 may approach 1.

Torsional vibrations, or waves, impressed on one end of the spring are propagated over a portion of the spring length at a velocity v_{tor} , given by

$$v_{\text{tor}} = \frac{a}{4\pi R^2} \left(\frac{E}{\rho} \right)^{1/2} \text{ turns/sec.} \quad (1)$$

where a is a constant for any given spring, R is the radius of any one turn of the spring, E is Young's modulus of elasticity for the material of which the spring is made, and ρ is the density of that material. If R is constant, then obviously v_0 , where

$$v_0 = \frac{a}{4\pi R_0^2} \left(\frac{E}{\rho} \right)^{1/2} \text{ turns/sec.}$$

is constant for any given spring, independent of frequency of the propagated waves. I have found, however, that when the wavelength of the vibrations includes

four turns of the spring along the tapered section, i.e., one turn of the spring encompassing $\lambda/4$, or 90° , of the signal cycle, one turn is caused to increase in radius while an adjacent turn is decreased in radius, and above the frequency corresponding to this wavelength the motion is no longer strictly torsional. More specifically, above this frequency, the mode of propagation of the waves changes from torsional to transverse.

The frequency at which this mode transition occurs may be determined from Equation 1. Since $v = \lambda f$, and $\lambda = 4$ turns of the spring at the frequency in question, then from Equation 1

$$f = \frac{a}{16\pi R^2} \left(\frac{E}{\rho} \right)^{1/2} \quad (2)$$

and the particular radius at which this occurs, hereinafter designated the break radius R_B is, from Equation 2,

$$R_B = \frac{1}{4} \left(\frac{a}{\pi f} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4} \text{ cm.} \quad (3)$$

As is apparent from Equation 3, R_B is a function of frequency, decreasing with increasing frequency. For transverse vibrations, or waves, the velocity of propagation along the spring is given by

$$v_{\text{trans}} = \frac{1}{R} \left(\frac{f a}{\pi} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4} \quad (4)$$

at R_B , the torsional velocity should equal the transverse velocity. Setting

$$v_{\text{tor}} = v_{\text{trans}}$$

or

$$\frac{a}{4\pi R^2} \left(\frac{E}{\rho} \right)^{1/2} = \frac{1}{R} \left(\frac{f a}{\pi} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4}$$

which gives

$$\frac{a}{4\pi R} = \left(\frac{f a}{\pi} \right)^{1/2} \left(\frac{\rho}{E} \right)^{1/4}$$

or

$$R = \frac{1}{4} \left(\frac{2}{\pi f} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4} \text{ cm.}$$

which agrees with the value for R_B obtained in Equation 3.

For a linear variation in helix radius from R_0 to R_1 ,

$$R_1 = R_0 + k N_{01} \quad (4a)$$

where k is the slope of the taper. Similarly,

$$N_B = \frac{R_B - R_0}{k} \quad (5)$$

where N_B is the number of the turn at which R_B occurs. Since

$$V = \frac{dn}{dt}$$

i.e., the rate of change of distance, measured in turns, with respect to time t , then, for the torsional mode the time delay is, from Equation 1,

$$T_{\text{tor}} = \frac{4\pi}{a} \left(\frac{\rho}{E} \right)^{1/2} \int_0^{N_B} R^2 dn$$

where $n=0$ is the turn having a radius R_0 at which the taper begins and N_B has the value obtained in Equation 5. Evaluating the integral gives

$$T_{\text{tor}} = \frac{4\pi}{3ka} \left(\frac{\rho}{E} \right)^{1/2} (R_B^3 - R_0^3) \text{ sec.} \quad (6)$$

Similarly, for the minimum constant diameter R_0 length of spring, the integration over the appropriate limits is simply

$$T_{\text{tor}} = \frac{4\pi R_0^2 N_0}{a} \left(\frac{\rho}{E} \right)^{1/2} \text{ sec.} \quad (7)$$

5

The total torsional time delay is, taking into account both ends of the spring, then

$$T_{\text{tor}} = \frac{8\pi}{3ka} \left(\frac{\rho}{E} \right)^{1/2} [R_B^3 - R_0^3 + 3kN_0R_0^2] \text{ sec.} \quad (8)$$

Using the same analysis to determine time delay in the transverse mode from Equation 4 gives

$$T_{\text{trans}} = \frac{1}{2k} \left(\frac{\pi}{fa} \right)^{1/2} \left(\frac{\rho}{E} \right)^{1/4} [R_1^2 - R_B^2] \text{ sec.} \quad (9)$$

for the spring portions between R_B and R_1 at either end, and

$$T_{\text{trans}} = N_1 R_2 \left(\frac{\pi}{fa} \right)^{1/2} \left(\frac{\rho}{E} \right)^{1/4} \text{ sec.} \quad (10)$$

for the spring length of radius R_1 . The total transverse time delay is, doubling Equation 9 and combining with Equation 10,

$$T_{\text{trans}} = \frac{1}{k} \left(\frac{\pi}{fa} \right)^{1/2} \left(\frac{\rho}{E} \right)^{1/4} [R_1^2 + 2N_1 R_1 k - R_B^2] \text{ sec.} \quad (11)$$

The total time delay of the spring is then

$$T_T = \frac{1}{k} \left(\frac{\pi}{fa} \right)^{1/2} \left(\frac{\rho}{E} \right)^{1/4} [R_1^2 + 2N_1 R_1 k - R_B^2] \text{ sec.} \\ + \frac{8\pi}{3ka} \left(\frac{\rho}{E} \right)^{1/2} [R_B^3 + 3kN_0 R_0^2 - R_0^3] \text{ sec.} \quad (12)$$

It will be seen that the total time delay, T_T , is a function of frequency.

The effect of the tapered spring on wave motion is as follows. Vibrational waves are excited in the spring in a non-dispersive mode, typically the torsional mode. At a particular helix radius, which differs for each frequency component of the complex wave, along an increasing taper portion the wave motion will undergo a transition from the non-dispersive to a dispersive mode, more specifically to the transverse mode. This mode transition radius is given by Equation 3, and as indicated, decreases with increasing wave frequency. Following the initial mode transition, the waves continue to propagate down the line in a transverse mode until a corresponding mode transition radius is encountered along a decreasing taper at which the wave motion, in accordance with its vibrational frequency, is converted back to the torsional mode. The result is that each wave component has a different delay time as a function of its frequency, as will be noted by reference to Equation 12. This result may similarly be viewed as a change in the effective length of the spring between mode transition radii for the various frequency components of the wave. Obviously, the spring may have several tapered portions rather than being tapered only at its end portions. Also, the taper may comprise a reduction in diameter from the ends toward the center of spring.

It will be recognized that the shape of the delay time versus wave frequency characteristic curve may be selected as desired for any spring by appropriate variation of the rate of taper, of R_0 and/or R_1 dimensions, or of the number of turns having an R_0 or R_1 radius. Delay time may alternatively be made a function of wave frequency by varying any of the parameters in Equation 3. Thus, for example, the wire radius of the spring may be altered over various portions of the spring, as opposed to varying the helix diameter, to produce results similar to those previously described. All of these variations and modifications are intended to be included within the scope of the present invention.

Referring now to FIGURES 2 and 3, an electromechanical driver transducer, illustrated generally at 10, is used for exciting torsional vibrations in spring 12. The tapered spring 12 has a pair of hooks 14, 15 located at either end thereof which engage the appropriate hooks 18, 19 for respective coupling to electromechanical

6

transducer 10 and to mechanicoelectrical pickup transducer 20. Transducer hooks 18, 19 are preferably of low compliance and may, for example, be seamless tubing of cold drawn Monel. Each hook 18, 19, is suitably fastened in respective annular permanent magnets 22 which may, for example be ceramic magnetic material of known construction. Wires 23 are respectively engaged at the ends of tubing hooks 18, 19 adjacent supports 30, 32, and are further secured to the supports. Wires 23 may, by way of example, be drawn from beryllium copper or Phosphor bronze of relatively small diameter, say 5 to 8 mils. The compliance of support wires 23 is preferably rather large since the low frequency response of the system is, to some extent, improved thereby. Similarly, the high frequency response of the system is improved as the moment of inertia of magnet 22 is decreased. Further, the damping of the vibrations in the spring 12 may be controlled by pieces 24 of damping material, an example being butyl rubber. Hence, the reverberation time, for a given piece of material, may be changed by variation of the distance, x , in FIGURE 2.

FIGURE 3 more clearly illustrates the preferred core shape for either the driver or the pickup transducer. Core 60 is preferably of formed magnetic-lamination construction, notched in the four corners as at 59 in FIGURE 2. Thus legs 63, 64 are formed by the narrowed sections of the core structure, forming an air gap 68 into which annular ceramic magnet 22 extends. Such construction is lower in cost than conventional "square-D" structure and provides reduced hum pickup.

A single coil 58 is wound about the magnetic core and terminates in a pair of terminals 61 and 62 to which appropriate electrical excitation or detection apparatus (not shown), respectively, may be operatively connected. For the driver transducer, for example, the winding is energized from an appropriate A.C. source and flux passes from magnetic paths of both side legs through gap 68, as illustrated, the flux alternating in accordance with the alternating character of the source output. Permanent magnet 22 oscillates in a torsional mode in response to the alternating flux passing through the gap to impress torsional waves at the oscillation frequency in spring 12.

To provide optimum coupling, and hence response, between tapered spring 12 and driver transducer 10 (or pickup transducer 20) the compliance and moment of inertia of the spring is arranged to equal the compliance and moment of inertia of the support wire and magnet.

Waves impressed upon the spring by the driver transducer travel, as hereinbefore explained, in the torsional mode of propagation until the break radius, R_B , at one end of the spring is reached, whereupon the waves are converted or translated to the transverse mode. In the transverse mode the components of the complex wave travel with a velocity proportional to their frequencies, and thus different time delays occur for the different components. Upon reaching the break radius, R_B , at the detection end of the spring, the vibrations undergo a transition back to the torsional mode and are subsequently detected at pickup transducer 20.

Each transducer is terminated in a known manner, as by impedance mismatch, to provide a rather large coefficient of reflection, for example, 80%, such that a portion of each wave, e.g., 20% in this example, is absorbed at the termination points and the larger portion, i.e., 80%, is reflected back along the spring.

The reflected portion of the wave propagates along the spring in the same manner as described above. The wave is repetitively detected each time it impinges upon the pickup transducer and is suitably converted to an electrical signal for subsequent conversion to audible sound. By virtue of such operation, each wave travels back and forth from one end of the spring to the other, the total travel time of each frequency component of

each wave being governed by the predetermined reverberation time of the spring. The delay line which has been described is thus dispersive, i.e., time delay is frequency sensitive, over a portion of its length (between break radii), and nondispersive, i.e., time delay is constant, over the remaining portions.

Referring to FIGURE 4a, there are two graphs, illustrating two similar pulses of audio frequency torsional vibrations respectively applied to a single, constant-diameter spring reverberation and to a single, tapered spring reverberator such as that illustrated in FIGURE 2. Referring to FIGURE 4b, there is illustrated a graph indicating the difference in multiple reflections occurring in a constant or uniform helical spring delay line and in the tapered spring delay line in accordance with the present invention both in response to the pulses shown in FIGURE 4. Each delay line was associated with the same transducers for excitation in the torsional mode and each was similarly terminated. The pulses illustrated at 80, representative of the constant spring response, are relatively sharply defined envelopes containing the reflected complex wave portions, and thus appear at the output of the system in periodic abrupt bursts, producing severe flutter. On the other hand, the reflected wave envelopes shown at 82, which appeared at the output of the tapered spring line, are smoothly varying by virtue of the functional dependence of time delay on frequency. It will be noted that each successive pulse in FIGURE 4b is slightly reduced in amplitude from its predecessor, indicating loss of energy during each reflection from the end of the line. Also, a repetitive on-off pulse can be conceived of such harmonic content which will result in the detected output pulses being overlapped for a tapered spring but not overlapped for a constant-diameter spring.

The dispersive characteristic of the tapered spring line is more clearly illustrated in FIGURE 5, again in comparison with the corresponding characteristic of the constant or uniform diameter spring line. As indicated, the tapered spring characteristic is a smoothly varying curve, time delay decreasing with increasing frequency. On the other hand, the constant diameter spring maintains a substantially constant delay versus frequency characteristic over the same audio range of interest. The shape of the time delay versus frequency curve for the tapered spring delay line may be altered by appropriate alteration of R_0 , R_1 , the number of turns with R_0 or R_1 radius, or by varying the rate of taper. Again, variation of any of the parameters appearing in Equation 12 will affect the shape of the time delay versus frequency characteristic.

FIGURE 6 depicts a representative electrical equivalent circuit of the driver transducer and spring end coupled thereto, shown in FIGURE 2. The driver coil and core are represented by an inductance across the input terminals. The moment of inertia of the permanent magnet corresponds to inductance I_m , coupled to the driver inductance. The compliance of the support wire inside the damping material corresponds to capacitance C_w , while the remaining compliance of the support wire is represented by capacitance C_{wt} . The compliance of the damping material and loss due to the damping material correspond to capacitance C_d and R_d , respectively. The equivalent circuit of the spring is a multiple section low pass filter connected across the series combination of I_m , C_{wt} and C_w . Each filter section comprises series inductance I_s and shunt capacitance C_s corresponding respectively to moment of inertia and compliance of the spring over each turn of spring length represented, the additional subscripts 0, 1, 2, etc. corresponding to the sections of spring having radius R_0 and each successive turn of changing diameter. Thus, the overall reverberator may be analyzed by means of an electrical analogy carried over for each portion of the electromechanical circuit.

FIGURE 7 illustrates one form of system, such as an electronic musical instrument, utilizing the previously described reverberation apparatus. A source of tone signals

85 provides an input to a channel containing appropriate amplification equipment 88. The channel may also include preamplifier and tone color filters 86 and other components suitable to the function. The output of this channel is fed to an electroacoustical transducer, such as loudspeaker 90. In this exemplary circuit arrangement, the reverberation apparatus 92 may be included in the same channel in series with a mechanical or electronic switch 95. By-passing the reverberation unit 92 and switch 95 is an amplifier 94, through which signal passes continuously. Thus, an audio output may be provided with or without reverberation.

In an alternative form (not shown) the reverberation apparatus may be connected to a second electroacoustical transducer, such as a second loudspeaker, with the switch arranged such that reverberation apparatus 92 may again be included or excluded from the output. It will be understood, of course, that the system depicted in FIGURE 7 is purely exemplary. The reverberator which has been shown and described may be used in any appropriate electroacoustical system or sound reproduction system such as electronic musical instrument, phonograph, tape recorder, and the like. It will also be apparent that a tapered spring delay line in accordance with the present invention may be used in other systems requiring dispersive lines. Delay lines find use, for example, in radar target indicators, and in memory circuits for computers. The present invention, therefore, while having preferred use in sound systems, is not to be limited thereby. Also, although the specific embodiment disclosed herein shows a helical spring, it will be understood that the turns of the spring may be of elliptical configuration, as well as square, hexagonal, octagonal, and the like.

Thus, although certain preferred embodiments have been shown and described, it will be apparent that various changes and modifications may be made without departing from the true spirit and scope of the present invention as defined by the appended claims.

I claim:

1. In an electroacoustic transmission system, a mechanical delay line, electromechanical transducer means responsive to applied electrical signals to excite vibrations in said line, mechanicoelectrical transducer means remote from said first-named means and responsive to said vibrations in said line to produce electrical signals representative thereof, said delay line comprising a single helical spring having a continuously variable helix diameter along at least a portion of the physical length thereof to vary the effective acoustic length of said spring as a function of the frequency of said vibrations, wherein the helix radius along at least a portion of the physical length of said spring is tapered monotonically from a first radius to a second radius, said radius having values such that vibrations undergo a change in mode of propagation along said tapered portions at a helix radius defined by

$$R = \frac{1}{4} \left(\frac{a}{\pi f} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4}$$

centimeters, where a is the radius of the spring wire, f is the frequency of said vibrations, E is Young's modulus of elasticity, and ρ is the density of said spring.

2. The combination according to claim 1 wherein said line is terminated in mismatched mechanical impedances to produce reflections of said vibrations.

3. The combination according to claim 1 wherein said electromechanical and mechanicoelectrical transducer means each comprise a square-D shaped magnetic core having a pair of substantially centrally located legs extending from opposed portions of said core to form a central air gap, a continuous winding wrapped about said core adapted to induce and to sense flux variations respectively in the magnetic path comprising said core and said gap, and permanent magnet means coupled to either end of said spring and extending into said gap to transmit and detect torsional vibrations in said spring.

4. A dispersive mechanical delay line comprising an elongated helical spring having a varying helix diameter, means for impressing mechanical vibrations in said spring, and further means remote from said first-named means for detecting said vibrations in said spring, the diameters of said helix including values sustaining distinct propagation modes of acoustic wave energy along said spring, wherein said helix diameter varies uniformly between different constant diameters, each frequency component of said vibrations undergoing a change from a non-dispersive to a dispersive propagation mode in the direction of increasing helix diameter and from dispersive to non-dispersive mode in the direction of decreasing helix diameter.

5. A dispersive mechanical delay line comprising an elongated helical spring having a varying helix diameter along at least a portion of its length, means for impressing mechanical vibrations in said spring at predetermined frequencies, and further means remote from said first-named means for detecting said vibrations in said spring, the diameter of said helix over said portion of its length including values effecting conversion as a function of frequency of vibration mode of acoustic wave energy along said portion of its length, the conversion of propagation mode being between torsional and transverse, wherein said helix diameter varies continuously between at least two different constant diameters over said at least a portion of its length, each frequency component of said vibrations undergoing a change from a non-dispersive to a dispersive propagation mode in the direction of increasing helix diameter and from a dispersive to a non-dispersive mode in the direction of decreasing helix diameter.

6. The combination according to claim 4, wherein said helix diameter is uniformly tapered for a minimum diameter adjacent either end of said spring.

7. The combination according to claim 6 wherein said first-named means is an electromechanical transducer coupled to one of said ends of said spring for impressing torsional vibrations in said spring, said torsional vibrations being converted to transverse vibrations for vibrational waves traveling in the direction of increasing helix diameter and back to torsional vibrations in the direction of decreasing helix diameter, and wherein said further means is a mechanicoelectrical transducer for detecting said torsional vibrations.

8. The combination according to claim 7 wherein said line is terminated at either end in an impedance discontinuity to partially reflect vibrations therefrom.

9. Apparatus for providing reverberation of electrical signals comprising electromechanical driver means having a movable element which vibrates in response to said electrical signals, mechanicoelectrical pickup means having a movable element, said pickup means generating electrical signals in response to vibration of its movable element, and a helical spring mechanically coupled between said movable elements for transmitting vibrations, the helix of said spring undergoing a smooth transition between differing values of diameter thereof selected for changing effective acoustic length of said spring as a function of the frequency of said vibrations, wherein said helix diameter varies substantially from first to second predetermined diameters along preselected portions of the length of said spring, and wherein said effective spring length varies as a function of frequency between helix diameters D, where

$$D \approx \frac{1}{2} \left(\frac{a}{\pi f} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4}$$

centimeters, a is spring wire radius, f is vibration frequency, E is Young's modulus for said spring wire, and ρ is the density of said spring wire.

10. A delay line comprising a single helical spring, torsional mode transducer means coupled to said spring for generating torsional wave motion in said spring, and

further torsional mode transducer means coupled to said spring at a point remote from said first-named transducer means for generating electrical signals in response to torsional wave motion in said spring, said spring including structure for converting vibrational mode between a dispersive and a nondispersive mode at different positions of said spring as a function of wave frequency over at least a portion of the length of said spring less than the spring length between said first-named and further transducer means, wherein said structure comprises portions of the spring length having a tapering helix diameter.

11. A delay line comprising a single helical spring, torsional mode transducer means coupled to said spring for generating torsional wave motion in said spring, and further torsional mode transducer means coupled to said spring at a point remote from said first-named transducer means for generating electrical signals in response to torsional wave motion in said spring, said spring including structure for converting vibrational mode between a dispersive and a nondispersive mode at different positions of said spring as a function of wave frequency over at least a portion of the length of said spring less than the spring length between said first named and further transducer means, wherein said structure comprises portions of the spring length having a tapering helix diameter and wherein said structure is varied in the wave frequency band governed by the radius R of the helix over said tapered portions in accordance with the relation

$$R = \frac{1}{4} \left(\frac{a}{\pi f} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4}$$

where f is the wave frequency, and a and ρ are respectively the radius and density of the spring wire, and E is Young's modulus of elasticity.

12. In an electroacoustic transmission system, a mechanical delay line, electromechanical transducer means responsive to applied electrical signals to excite vibrations in said line, mechanicoelectrical transducer means remote from said first-named means and responsive to said vibrations in said line to produce electrical signals representative thereof, said delay line comprising a single helical spring having at least one continuously modified parameter along at least a portion of the physical length thereof to vary the effective acoustic length of said spring as a function of the frequency of said vibrations, wherein said at least one continuously modified parameter of said spring varies monotonically from a first value to a second value over said portion of the physical length of said spring, said values being such that said vibrations undergo a change in mode of propagation along said portion at helix positions defined as a function of frequency by

$$R = \frac{1}{4} \left(\frac{a}{\pi f} \right)^{1/2} \left(\frac{E}{\rho} \right)^{1/4}$$

where R is the helix radius, a is the radius of the spring wire, f is the frequency of said vibrations, E is Young's modulus of elasticity, and ρ is density of said spring wire, and said parameters are R , a , E and ρ .

13. In a reverberation system, a helical spring delay line having an input end and an output end; a transducer for driving said input end in torsional vibrational mode in response to a wide band electrical signal; a further transducer for deriving output signal from said output end in response to torsional vibrations; said helical spring delay line having a uniformly increasing helix diameter over a plurality of turns of the helix from a first diameter adjacent said input end to a second diameter, said second diameter being maintained substantially constant over a plurality of turns of the helix, and a uniformly decreasing helix diameter over a plurality of turns of the helix from said second diameter to substantially said first diameter adjacent said output end; the

11

distinct and different diametral values over each of the increasing and decreasing diameter portions of said helical spring delay line, as encountered by the traveling vibrations, being selected to provide a transition in vibrational mode therealong, from torsional to transverse mode at each increasing diameter portion and from transverse to torsional mode at each decreasing diameter portion, as a function of the frequency of the vibrations.

14. A reverberator for mechanical transmission of signals within a band of frequencies; said reverberator including signal input means for applying signals thereto in a first transmission mode, and signal output means for detecting signals transmitted thereby; said reverberator further including an elastic member coupled to said input and output means and having a parameter, selected from one of the dimensional parameters thereof, with a continuous range of distinct values, each different from the others, throughout a portion of the length of said member; said range of distinct values of said parameter being selected to produce, in response to signals transmitted along said member, a change in mode of transmission of said signals between said first mode and a second transmission mode as a function of signal frequency over said band of frequencies, so that the transmission mode change is effected at a different value of said parameter for each frequency, said member having a further portion of the length thereof wherein said parameter varies over said range of values in reverse fashion to that in the first-mentioned portion, to effect a reversion in the transmission mode of said signals to the mode existing prior to said change.

15. In a reverberation system, a mechanical delay line, said mechanical delay line including a helical wire spring, a source of a band of frequencies, means responsive to said band of frequencies for inducing mechanical vibration in said helical wire spring, said helical wire spring including at least a portion taken lengthwise along said wire spring over which at least one spring parameter is continuously variable, and wherein the spring parameters include wire radius, and helix radius, and wherein the range of parameter variation generates modes of vibration which are different for different mechanical vibration frequencies within said band of frequencies for different combinations of values of said parameters, in response to the mechanical vibrations induced by said means.

16. A reverberation simulating device comprising,
a base member,
a pair of supports spaced from each other on said base member,
a tapered helical spring having relatively smaller-diameter turns at either end thereof and relatively larger diameter turns at the center thereof,
a pair of support wires suspending said spring between said supports,

12

a pair of annular permanent magnets mounted on said pair of support wires respectively.

a pair of electromagnetic structures mounted on said base so as to encompass said magnets, said electromagnetic structures comprising each,

a core member having two legs forming an air gap for one of said magnets,

a coil encircling at least one of said legs, and leads extending from each of said coils.

17. In an electronic organ having in combination, generating means for generating electrical signals corresponding in characteristics to musical tones, and output means coupled to said generating means for converting said electrical signals to said musical tones, a reverberation simulating device coupled between said generating means and said output means, said reverberation device comprising

a base member,

a pair of supports spaced from each other on said base member,

a tapered helical spring having relatively smaller-diameter turns at either end thereof and relatively larger diameter turns at the center thereof,

a pair of support wires suspending said spring between said supports,

a pair of annular permanent magnets mounted on said pair of support wires respectively,

a pair of electromagnetic structures mounted on said base so as to encompass said magnets, said electromagnetic structures comprising each,

a core member having two legs forming an air gap for one of said magnets,

a coil encircling at least one of said legs, and leads extending from each of said coils,

the leads from one of said coils being coupled to said generating means and the leads from the other of said coils being coupled to said output system.

References Cited by the Examiner

UNITED STATES PATENTS

1,678,116	7/28	Harrison	333—71
2,230,836	2/41	Hammond	179—1
2,375,004	5/45	Knowles	333—30
2,853,145	9/58	Martin	181—31
2,913,680	11/59	Porter	333—71
2,967,447	1/61	Hanert	84—1.26
3,092,792	6/63	Daniel	333—30
3,136,853	6/64	Bissonette	179—1

HERMAN KARL SAALBACH, *Primary Examiner.*

ELI LIEBERMAN, *Examiner.*