May 2, 1961 J. E. MAY, JR 2,982,926

DELAY LINE

Filed July 6, 1959

FIG. 1

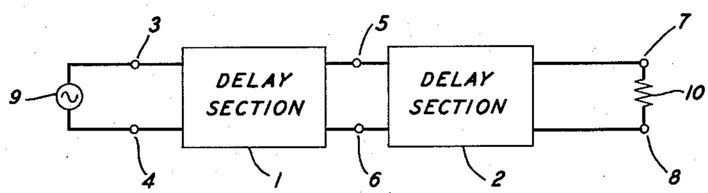


FIG. 2

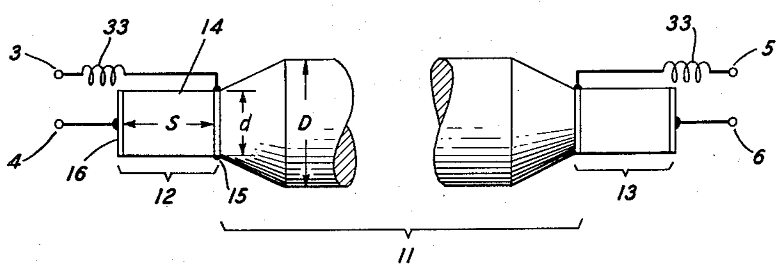


FIG. 3

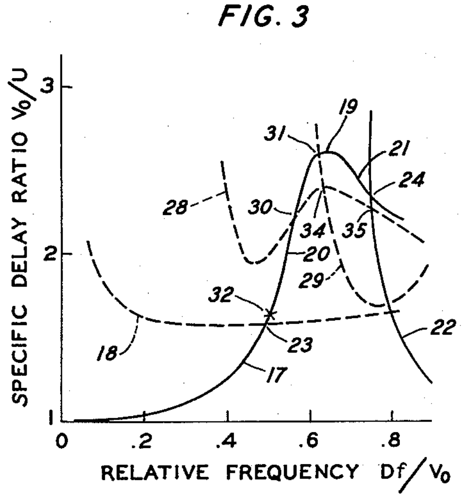
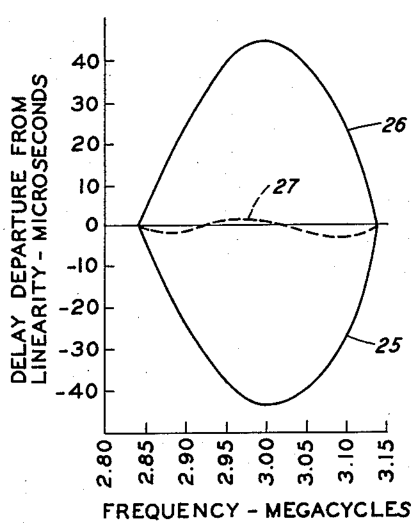


FIG. 4



INVENTOR
J. E. MAY JR.
BY Ralph T. Holcomb
ATTORNEY

United States Patent Office
2,982,926
Patented May 2, 1961

1

2,982,926

DELAY LINE

John E. May, Jr., Whippany, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Filed July 6, 1959, Ser. No. 825,326
10 Claims. (Cl. 333—30)

This invention relates to wave transmission and more particularly to an ultrasonic delay line comprising a plurality of solid sections.

An object of the invention is to delay an electrical signal by a time which is substantially a linear function of frequency and has a positive, negative, or zero slope. A further object is to avoid the propagation of unwanted modes which give rise to spurious signals in the electrical output.

In wave transmission systems, it is sometimes desired to introduce a delay characteristic which is linear over a considerable frequency range and has a positive, negative, or zero slope. Ultrasonic delay lines are well suited for this purpose. In order to improve the performance of the delay line, it is desirable to avoid spurious signals.

The delay line in accordance with the present invention meets these requirements by employing two or more sections of solid, ultrasonic transmission line connected in tandem. Each of the sections has a transverse dimension comparable to the acoustic wavelength of the transmitted signal. The delay-frequency characteristic of one of the sections has a positive curvature, and that of a second section a negative curvature, over the frequency range of interest. The curvatures are so chosen that the over-all characteristic is substantially linear and has the desired slope.

The sections may employ the same or different modes of propagation. Modes are chosen which provide the desired curvatures. It is also helpful to choose a mode which can be excited preferentially. Some modes have a characteristic with one or more points of inflection, and hence exhibit both positive and negative curvatures. These include all longitudinal and flexural modes. Therefore, one of these modes may be used in both sections. However, the characteristics of the shear and torsional modes above the lowest have only a positive curvature. Consequently, if one of these modes is used in one of the sections, the second section must employ some other mode exhibiting a negative curvature in order to obtain a linear over-all characteristic.

Spurious signals to be avoided may be those associated with undesired modes of propagation, or non-propagated modes associated with resonance effects at one or more frequencies. The desired mode may be favored over the undesired by choosing the size of the electromechanical transducer so that its displacement configuration most closely approximates that of the desired mode. Regions where the characteristic of the desired mode coincides with that of an undesired mode are avoided.

A typical example of a composite delay line in accordance with the present invention is presented. The structure comprises two sections connected in tandem. Each section includes a length of wire with associated electromechanical transducers at the ends. The first longitudinal mode is used in each section. The delay-frequency characteristic of one of the sections has a positive curvature and that of the other a negative curvature over the frequency range of interest. These are so chosen that the over-all characteristic is substantially linear over the range and has a positive slope. Since the slope is not zero, the line is dispersive. In order to favor the first longitudinal mode over the other unwanted modes, the transducer comprises a cylinder of piezoelectric material having a smaller diameter than the wire line. Also, for the same reason, the adjoining ends of the crystal and the wire are made as nearly concentric as possible. To minimize reflection, the line preferably tapers at the end to the diameter of the transducer. Points where the characteristic of the first longitudinal mode is crossed by that of the second longitudinal mode, or the first, second, or third flexural mode, are avoided. Points at which nonpropagated, resonance effects appear are also avoided.

The nature of the invention and its various objects, features, and advantages will appear more fully in the following detailed description of a typical embodiment illustrated in the accompanying drawing, of which

Fig. 1 is a block diagram showing a delay line in accordance with the invention comprising two sections connected in tandem;

Fig. 2 is a side view, with the central portion removed, of one of the sections of delay line used in Fig. 1;

Fig. 3 is a plot of the specific delay ratio versus relative frequency for the first two longitudinal and the first three flexural modes in a solid cylindrical line; and

Fig. 4 shows plots of the departure from linearity versus frequency for a two-section delay line in accordance with the invention, and for each section.

Fig. 1 shows a composite delay line comprising two sections **1** and **2** connected in tandem between a pair of input terminals **3—4** and a pair of output terminals **7—8**, with intermediate terminals **5—6**. A source **9** of alternating-current signals to be delayed is connected to the input terminals, and a suitable load **10** to the output terminals.

In the present example, it is assumed that each delay section employs a length of wire-type delay line operating in the first longitudinal mode. Fig. 2 shows, to an enlarged scale, the preferred structure of section **1**. Section **2** may be of similar construction, but with different dimensioning, as explained below. The section comprises a solid, cylindrical rod or wire **11** with two substantially identical electromechanical transducers **12** and **13** connected to its ends. To save drawing space, only the ends of the wire **11** are shown. The missing portion may be straight or it may be coiled in any convenient manner. The wire **11** has a uniform diameter D except at the ends, which taper to a smaller diameter d. The transducer **12** comprises a cylinder **14** of piezoelectric material, such as barium titanate ceramic, having a length S approximately equal to a half wavelength in the material at the midband frequency. Its ends are covered by the electrodes **15** and **16**, which are connected, respectively, to the terminals **3** and **4**. The inductor **33** is connected in series with the cylinder **14** to widen the transmission band of the transducer by providing a better electrical impedance match. Its inductance is chosen to annul the effect of the reactive component of the input impedance of the transducer, at approximately the midband frequency.

When the signal is applied to the terminals **3** and **4**, the transducer **12** excites the first longitudinal mode in the line **11**. The diameter d of the driving cylinder **14** is made smaller than the diameter D of the line **11**, and the cylinder is carefully centered on the end of the line, to reduce the generation of undesired flexural and other modes. To reduce reflection, the ends of the line **11** are preferably tapered at an angle of about 30 degrees.

It will now be explained how to determine the length and diameter of the delay line section **11**. The delay-frequency curves of Fig. 3 are useful for this purpose.

The ordinates represent the specific delay ratio, which is the ratio of the bar velocity V_0 to the group velocity U. V_0 is the square root of the ratio of Young's modulus to the density of the wire. The abscissas are the frequency multiplied by the ratio of the diameter D of the wire to V_0. The curves **17** and **22** are for the first and second longitudinal modes, respectively, and the curves **18**, **28**, and **29** for the first, second, and third flexural modes, respectively. It is seen that the curve **17** has a maximum at the point **19**, with a positive slope below this frequency and a negative slope above. Also, the curve has two points of inflection **20** and **21** between which the curvature is negative. Outside of this region, the curvature is positive. The curves shown are for aluminum with a Poisson's ratio of 0.33.

The curves **18**, **28**, **29**, and **22** cross the curve **17** at the points **23**, **30**, **31**, and **24**, respectively. At the point **32** designated by X in Fig. 3, there is distortion in the amplitude and phase characteristic of the delay line, apparently caused by coupling with an interfering mode. All of these points are critical and are to be avoided as operating regions for the delay sections. However, the shapes of the curves and the relative positions of the critical points vary with Poisson's ratio. For example, for a nickel-iron alloy with a Poisson's ratio of 0.23, the crossing point **23** occurs at approximately the same position with respect to the inflection point **20**, but the critical point **32** occurs at a lower value of relative frequency.

In the present example, each of the delay sections **1** and **2** operates on a portion of the curve **17**. In order to get a linear over-all delay-frequency characteristic, one of the sections operates somewhere between the lower inflection point **20** and the upper inflection point **21**, where the curvature is negative. The other section operates outside of this region, where the curvature is positive. To get a maximum positive slope, both of the sections will operate on the portion of the curve below the point **19**, where the slope is positive. For a maximum negative slope, the portion above the point **19**, with negative slope, is utilized. However, if maximum slope is not essential, only the section having the greater delay change need have the desired slope, either positive or negative. The other section may be of either slope. To get zero slope for the over-all characteristic both the slopes and the curvatures of the portions of the curve **17** used in the two sections **1** and **2** must differ in sign. Therefore, a portion below the point **20** may be combined with a portion between the points **19** and **21**, or a portion above the point **21** may be combined with a portion between the points **19** and **20**. In all cases, the crossing points **23**, **30**, **31**, and **24**, and also the critical point **32**, are avoided in selecting the portion of the curve **17** to use.

In the present example, a substantially linear characteristic between 2.84 and 3.14 megacycles per second with approximately maximum positive slope is obtained by using two lengths of aluminum wire with a Poisson's ratio of 0.33. The section **1** operates on the curve **17** in a region below the point **23** where both slope and curvature are positive. The section **2** uses the region of positive slope but negative curvature between the points **30** and **31**. The section **1** has a diameter of 0.027 inch and a length of 1868.4 inches. Its delay increases from 11,375 to 12,408 microseconds over the band, and is 11,857 at the midband frequency of 2.99. The section **2** has a diameter of 0.040 inch, a length of 157.1 inches, and delays of 1,766 and 1,996 microseconds, respectively, at the lower and upper edges of the band.

The curves in Fig. 4 show the performance of the composite delay line. The curve **25** gives the departure of the section **1** from linearity, and the curve **26** gives the departure of the section **2**. Each has a maximum departure of about 44 microseconds, near midband, but the departures are of opposite sign. The deviation of the combination, given by the broken-line curve **27**, has a maximum of less than four microseconds over the band, and is zero at the edges and at two intermediate points. The over-all delay increases from 13,141 to 14,404 microseconds over the band. There is thus achieved a dispersive delay characteristic that is substantially linear over a comparatively wide frequency range and has a comparatively large positive slope.

As already mentioned, the two sections do not need to use the same mode of propagation. For example, a linear over-all delay characteristic with negative slope may be obtained by using a portion of the curve **18**, for the first flexural mode, to the left of the point **23** in one section and a portion of the curve **17**, for the first longitudinal mode, between the points **19** and **21** in the other section. Or, alternatively, a portion of the curve **28**, for the second flexural mode, between the crossing points **34** and **35** may be used in the second section.

It is to be understood that the above-described arrangement is only illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A composite delay line with a substantially linear delay versus frequency characteristic over a comparatively wide frequency range comprising two sections connected in tandem, each of the sections including a solid, ultrasonic transmission line and associated electromechanical transducers at the ends thereof, one of the transmission lines having a characteristic of specific delay ratio versus relative frequency for its operating mode which has a positive curvature over the band and the other transmission line having a characteristic of specific delay ratio versus relative frequency for its operating mode which has a negative curvature over the band.

2. A delay line comprising two solid, ultrasonic transmission lines connected in tandem, one of the transmission lines having a characteristic of specific delay ratio versus relative frequency for a selected mode of propagation which has a positive curvature over a band of frequencies, the other transmission line having a characteristic of specific delay ratio versus relative frequency for a selected mode of propagation which has a negative curvature over the band, the curvatures being chosen to provide a linear overall delay-frequency characteristic, and the utilized portions of the characteristics being free from points of interference due to unwanted modes.

3. A composite delay line with a delay versus frequency characteristic which is substantially linear over a frequency range and has a positive slope comprising two lengths of solid transmission line connected in tandem, the first length providing the major delay change and having a characteristic of specific delay ratio versus relative frequency with a positive slope over the range and the second length having a characteristic of specific delay ratio versus relative frequency with a curvature which differs in sign from that of the first length over the range.

4. A delay line in accordance with claim 3 in which the second length has a positive slope over the range.

5. A delay line in accordance with claim 3 in which the second length has a negative slope over the range.

6. A composite delay line with a delay versus frequency characteristic which is substantially linear over a frequency range and has a negative slope comprising two lengths of solid transmission line connected in tandem, the first length providing the major delay change and having a characteristic of specific delay ratio versus relative frequency with a negative slope over the range and the other length having a characteristic of specific delay ratio versus relative frequency with a curvature which differs in sign from that of the first length over the range.

7. A delay line in accordance with claim 6 in which the second length has a negative slope over the range.

8. A delay line in accordance with claim 6 in which the second length has a positive slope over the range.

9. In combination, two sections of solid, ultrasonic transmission line connected in tandem, the sections having characteristics of specific delay ratio versus relative frequency which differ from each other both in the sign of the slope and the sign of the curvature over a frequency range, and the utilized portions of the characteristic being so selected that the over-all delay versus frequency characteristic of the combination is substantially flat over the range.

10. A dispersive delay line comprising two lengths of ultrasonic transmission line connected in tandem, each of the lengths being adapted to operate in the first longitudinal mode and having a characteristic of specific delay ratio versus relative frequency with a point of inflection, one of the lengths operating above the point, the other length operating below the point, and the operating portions of the characteristic for the two lengths being so chosen that the over-all delay-frequency characteristic is substantially linear over a range of frequencies.

References Cited in the file of this patent

UNITED STATES PATENTS

2,181,499	Wheeler	Nov. 28, 1939
2,697,936	Farrow	Dec. 28, 1954
2,806,155	Rotkin	Sept. 10, 1957