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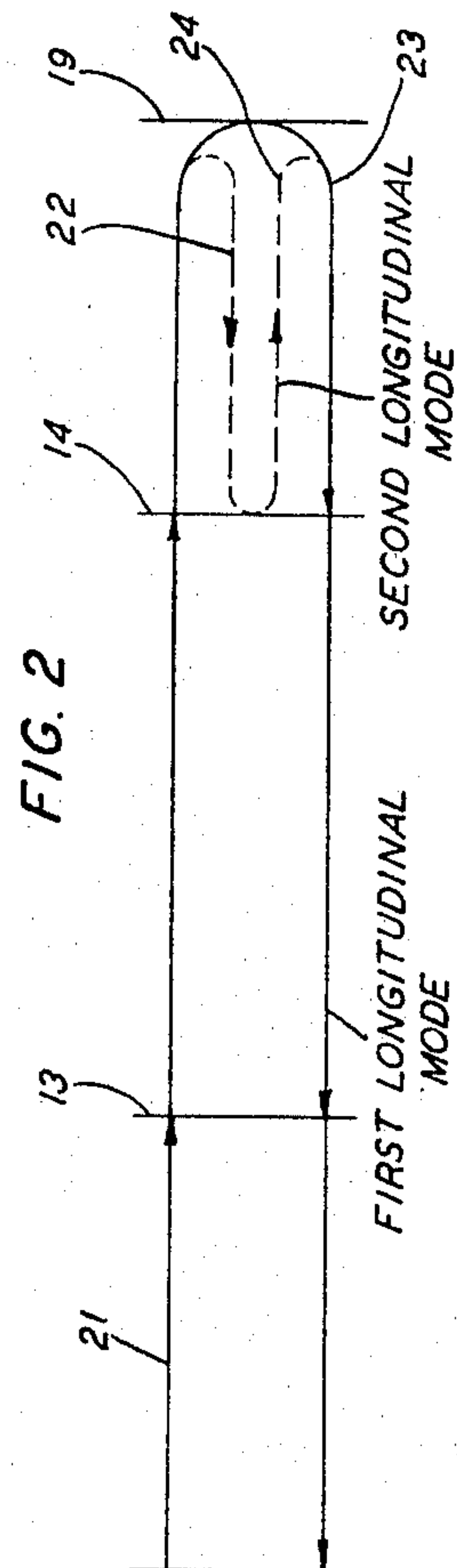
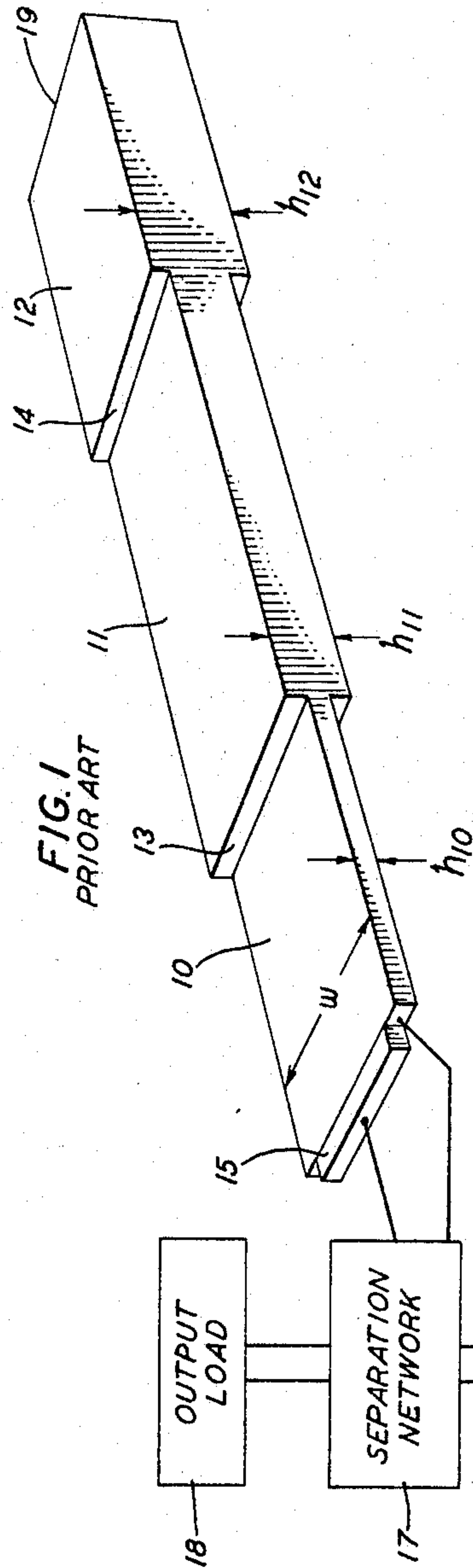
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ULTRASONIC DELAY DEVICE

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2 Sheets-Sheet 1



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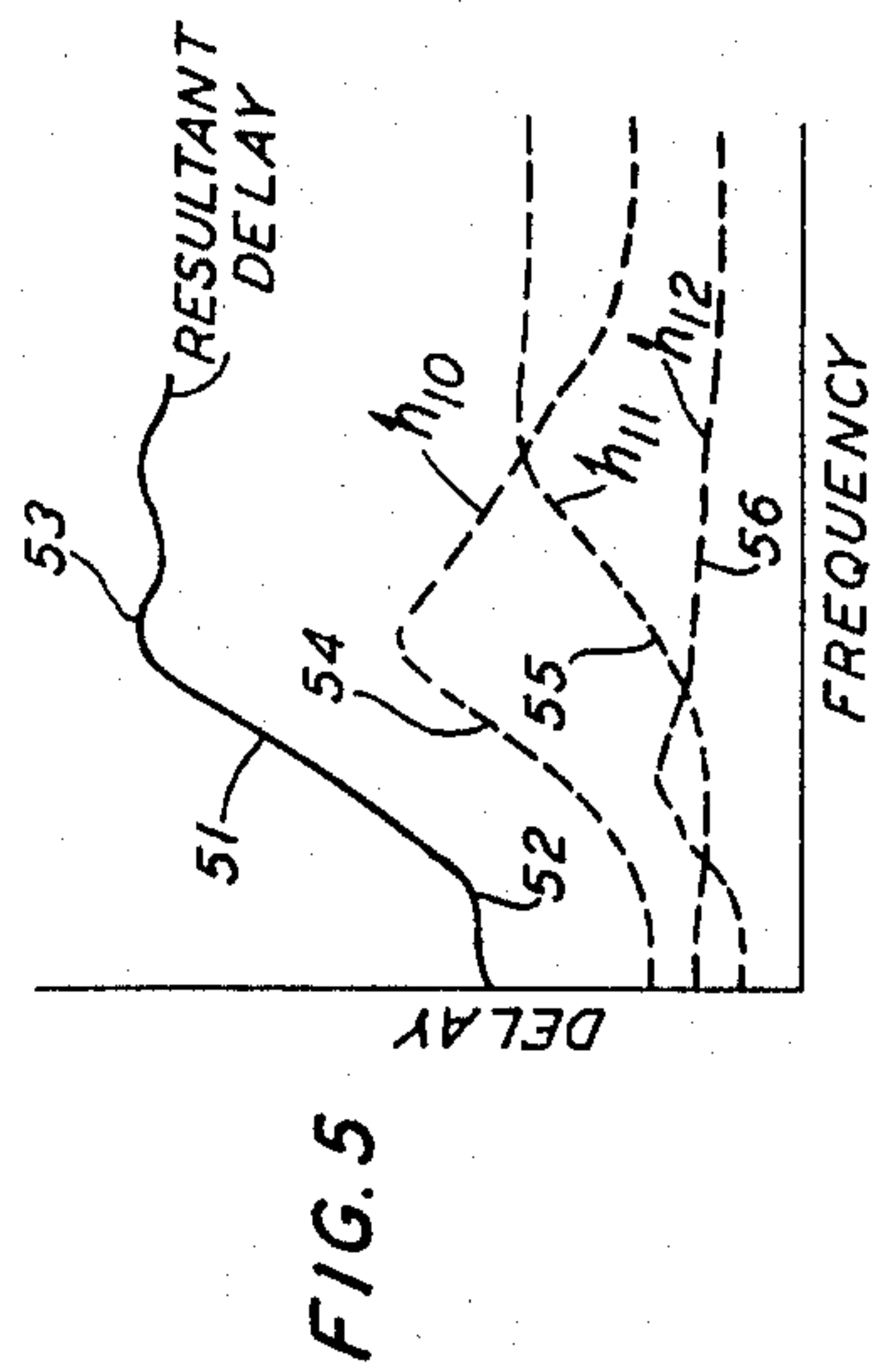
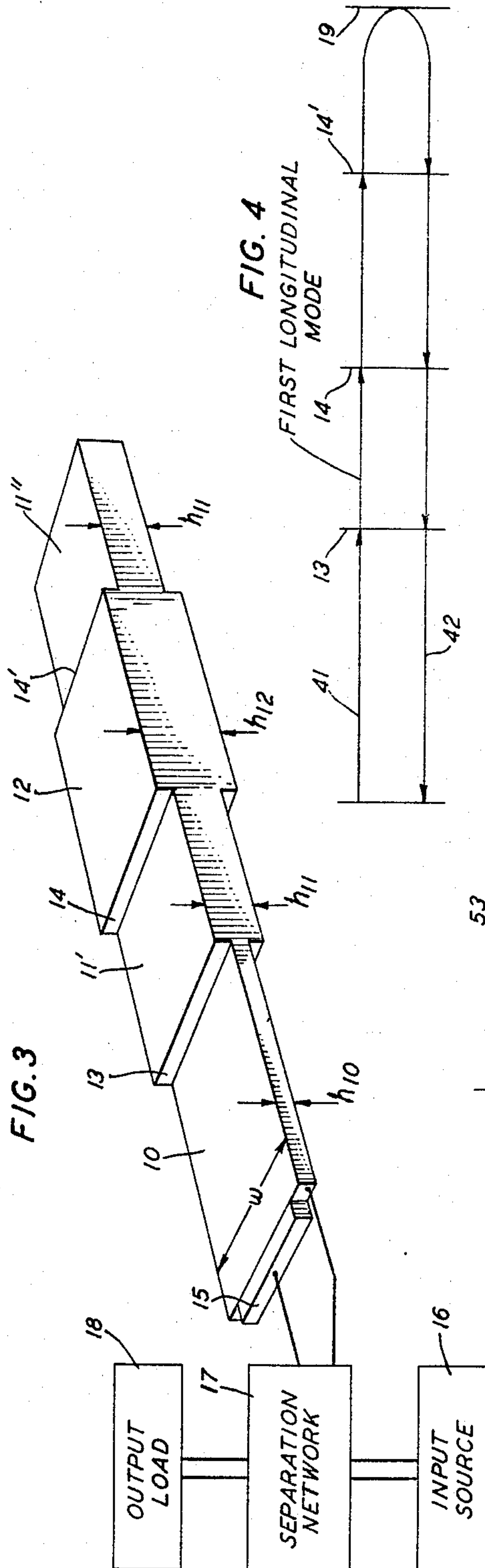
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ULTRASONIC DELAY DEVICE

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1 Claim. (Cl. 333—30)

This invention relates to delay devices and more particularly to ultrasonic delay lines having special delay versus frequency characteristics.

Dispersive delay lines, that is, those having a delay that varies according to some function with frequency are well known and their usefulness in numerous applications is recognized. Typical of this form is the strip delay line using the first longitudinal mode of propagation which may be designed to produce a delay characteristic that increases in an approximately linear relationship with frequency over a given band.

It has been pointed out by A. H. Fitch in copending application Serial No. 287,249, filed June 12, 1963, that substantially any dispersive characteristic may be synthesized by a plurality of successive first longitudinal mode strip delay sections having different thickness dimensions. However, it has been found that design of the most useful linear delay versus frequency characteristic requires that at least one of these sections have a thickness so large that the second longitudinal mode can be supported in that section even though the remaining sections have thicknesses small enough that the second mode is cut off. With the ordinary arrangement of sections, the presence of the second longitudinal mode causes undesired and spurious responses.

It is therefore an object of the present invention to reduce these undesired and spurious responses.

In accordance with the invention it has been recognized that spurious signals are generated by conversion of first longitudinal mode energy into second longitudinal mode energy at either the transducer or the reflecting end faces or both, but not at mere dimensional discontinuities along the line between the sections of different thickness. The latter exception is contrary to what would have been expected from any analogy drawn from electromagnetic waves propagating in conductivity-bounded waveguides wherein any discontinuity produces reflections. Therefore, it is proposed in accordance with the present invention, to isolate end faces and transducers by sections of delay line having thickness dimensions too small to support the second longitudinal mode and thereby avoid its generation at any point along the composite line.

These and other objects, the nature of the present invention, its various features and advantages will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a showing, partly in schematic and partly in perspective, of a single-ended, three-section dispersive delay line in accordance with the prior art;

FIG. 2 is a schematic showing of the propagation paths of different modes in the embodiment of FIG. 1;

FIG. 3 is a showing of a single-ended, four-section dispersive delay line in accordance with the invention;

FIG. 4 is a schematic showing of propagation paths in the embodiment of FIG. 3; and

FIG. 5 shows delay versus frequency characteristics typical of the invention and of the prior art.

Inasmuch as it will be helpful in understanding the principles of the present invention to compare it with the prior art, a device in accordance with prior construction is illustrated in FIG. 1 and will be described along with a device in accordance with the invention as shown

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in FIG. 3. Corresponding reference numerals will be used to designate corresponding components.

Referring therefore alternatively to FIG. 1 or 3, there is shown a delay medium having at least three successive portions 10, 11 and 12. Each portion is in the form of a strip having parallel major surfaces spaced apart by a small thickness dimension equal to h_{10} in section 10 and different dimensions h_{11} and h_{12} in sections 11 and 12 so chosen to produce the desired delay versus frequency characteristic as will be set forth hereinafter. Parallel minor surfaces are spaced apart by a width dimension w that is large compared to either h_{10} , h_{11} or h_{12} . The portions are arranged successively with one end of each section connected rigidly to an end of the succeeding section in coaxial relationship with each other so that steps or discontinuities 13 and 14 are formed at their junctions. Ideally, all sections should be integrally formed from an isotropic material such as glass or vitreous silica, but polycrystalline materials such as metallic alloys have proven satisfactory provided grain size is sufficiently small compared to the wavelength of the elastic wave carried by the strip.

The difference between FIGS. 1 and 3 will be seen to reside in the arrangement of the sections. In FIG. 1 the usual prior art arrangement of the sections is shown in which the sections are arranged with successively increasing thickness dimension h_{10} , h_{11} and h_{12} , respectively, while in FIG. 3 two sections 11' and 11'' respectively preceding and following section 12 replace single section 11 preceding section 12 in FIG. 1. For comparison, sections 11' and 11'' of FIG. 3 have a combined length equal to section 11 of FIG. 1. Sections 11' and 11'' need not be equal in length to each other provided that section 11'' has a length at least two or three wavelengths of the ultrasonic energy. A length substantially shorter than this would not provide the isolation to be described hereinafter.

A particular feature of the present invention resides in the maximum thickness of sections 10 and 11'' in FIG. 3. Specifically, dimension h_{11} of section 11'' is less than the cut-off thickness for the second longitudinal mode in strip line at the highest frequency in the band of interest. The dimension h_{10} of section 10 is also less than the second mode cut-off thickness. The cut-off thickness is very roughly equal to one-half wavelength of the second longitudinal mode in the particular material for the frequency referred to as the cut-off frequency. In this respect, ultrasonic cut-off is closely analogous to the cut-off condition of electromagnetic wave energy in conductivity-bounded waveguides. For a given thickness, frequencies less than the cut-off frequency will not support free propagation of the second longitudinal mode in the structure. Similarly, for a given frequency the second longitudinal mode cannot freely propagate in a structure having a thickness less than the cut-off thickness. A more accurate definition of cut-off depends upon very complicated transcendental equations of wave motion, extensive treatment of which may be found in the literature. Most helpful in the present connection is the analysis "The Application of the Theory of Elastic Waves in Plates to the Design of Ultrasonic Dispersive Delay Lines," by T. R. Meeker, appearing in the I.R.E. International Convention Record, 1961, Volume 9, Part 6, pages 327-333.

In both FIG. 1 and FIG. 3, means are provided at the end face of the thinner section 10 for coupling an electrical input signal with an ultrasonic wave in section 10 and, in turn, for coupling an ultrasonic wave to an electrical output load. As illustrated, the source of input signals is represented by 16 and the output load by 18. These circuits are coupled together by any suitable separation network 17 which is capable of discriminating between the input and the output signals. For example, if

the input is a source of pulses, network 17 can be a simple gating circuit which discriminates on the basis of time. On the other hand, network 17 may be one of any of the various forms of circulators which discriminate on the basis of direction of propagation. Network 17 is, in turn, coupled to a conventional piezoelectric ceramic transducer 15 in the form of a rectangular bar bonded to one end face of strip 10 using standard techniques. Transducer 15 is poled, provided with electrodes, and suitably bonded to section 10 in accordance with any of several transducer designs known to produce and respond to vibrations in a thickness-longitudinal mode. Accordingly, when the transducer is excited by an alternating voltage, such as a pulse of wave energy applied from network 17 connected to the electrodes, a thickness-longitudinal mode of vibration is induced therein. Conversely, an elastic wave motion in the strip generates an electrical signal that is delivered by network 17 to load 18.

The relative thicknesses of all sections and their lengths are chosen to synthesize a desired delay versus frequency characteristic as shown on FIG. 5. Thus, curve 51 represents the synthesized delay characteristic desired for either the delay line in FIG. 1 or FIG. 3 and may be seen to have a substantially linear delay versus frequency characteristic extending from point 52 to substantially point 53. Characteristic 51 is the resultant of the several contributions of sections 10, 11 and 12 of FIG. 1 or 10, 11' 11'' and 12 of FIG. 3 as represented by the dotted characteristics 54 through 56. Further treatment of this synthesis may be found in the above-mentioned copending application of A. H. Fitch.

In the usual case, the characteristic of the thickest section or perhaps for the thickest several sections required for a desired synthesis is obtained by a thickness dimension that is greater than the cut-off thickness for the second longitudinal mode as defined above. That is, in order to produce characteristic 56 of FIG. 5, h_{12} of section 12 must be greater than the second longitudinal mode cut-off. When this is the case the presence of spurious signals had been observed and was recognized as a serious complication even though the origin of these signals was not understood.

Initial analysis would suggest that the second longitudinal mode could not produce spurious signals in the line since the thinner sections thereof were cut off for this mode even though other sections could support its propagation. As a result of applicant's analysis, however, it has been determined that the spurious signals arise from conversion of some first longitudinal mode energy into second longitudinal mode energy and then reconversion at a later time into first longitudinal mode. Furthermore, it has been recognized that this conversion takes place either initially at the transducer or at a completely reflecting end face but not at the discontinuity between sections of different thickness. This may be seen by reference to FIG. 2 in which the propagation paths of both modes in the structure of FIG. 1 are represented. Thus, the first longitudinal mode is excited by the direct action of transducer 15 as represented by wave path 21. The signal propagates through sections 10, 11 and 12 until it reaches the reflecting end face 19 of section 12. Here some of its energy is converted into second longitudinal mode energy as represented by wave path 22, while the remainder is reflected as first longitudinal mode energy as represented by wave path 23. The second longitudinal mode returns through section 12 until it reaches the first section having a dimension less than the second longitudinal mode cut-off whereupon it is completely reflected since it cannot enter the restricted dimension of the section. Assume that in FIG. 1 this reflection occurs at discontinuity 14 between sections 11 and 12 as shown by path 24. Returning to end face 19, part of the energy is converted back into first longitudinal mode energy traveling toward transducer 15 and arriving as a spurious signal at a time delayed from the main signal by twice

the delay of section 12. Further multiple reflections of second longitudinal mode energy within section 12 result in other spurious signals. While the foregoing difficulties have been described with reference to a single-ended delay line driven from the smaller end, similar spurious signals are produced if the line is driven from the larger end or has separate input and output transducers at the respective ends.

The improvement afforded by the present invention may be seen from FIG. 4. The first longitudinal mode is excited as in FIG. 2 and travels toward the reflecting end face 19 as represented by path 41. Even though section 12 is large enough to support the second longitudinal mode, no energy is converted into this mode at either discontinuity 14 or 14'. Upon reaching face 19 energy is reflected but none of it is converted into second longitudinal mode energy because section 11'' is too thin to support this mode. The undistorted signal therefore returns to the input as represented by path 42.

Sections 11' and 11'' of FIG. 3 have been illustrated as having equal thickness dimensions both equal to h_{11} of FIG. 1 and as having a combined length equal to the length of section 11 only to illustrate how the sections of FIG. 1 may be redistributed in accordance with the invention to obtain the same synthesized delay characteristic and yet avoid the generation of spurious signals. It should be apparent, however, that section 11' of FIG. 3 may have any thickness including one greater than the second longitudinal mode cut-off thickness. Furthermore, it should be understood that the structure of FIG. 3 may be operated with transducers at either end or at both ends without altering either its delay versus frequency characteristic or its spurious signal response.

In all cases it is to be understood that the above-described arrangements are merely illustrative of a small number of the many possible applications of the principles of the invention. Numerous and varied other arrangements in accordance with these principles may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

In combination, an elongated delay line of ultrasonic transmission material having energy-guiding major surfaces that are spaced from each other to define a relatively small thickness therebetween, said line including end portions and a center portion between said end portions, said thickness in at least a part of said center portion being greater than the cut-off thickness of the second order longitudinal mode of elastic wave motion in said line, said thickness in said end portions being less than said cut-off thickness, and a thickness-longitudinal-mode transducer mounted on at least one of said end portions for coupling between electrical signals and longitudinal modes of elastic wave motion on said line, said portions each having significant lengths which together with the thicknesses thereof are functions of a composite predetermined delay characteristic unique to the first order longitudinal mode of elastic wave motion along the sum of said portions whereby said characteristic is introduced to wave motion produced by said transducer.

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