

May 1, 1951

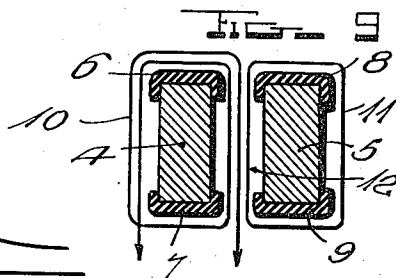
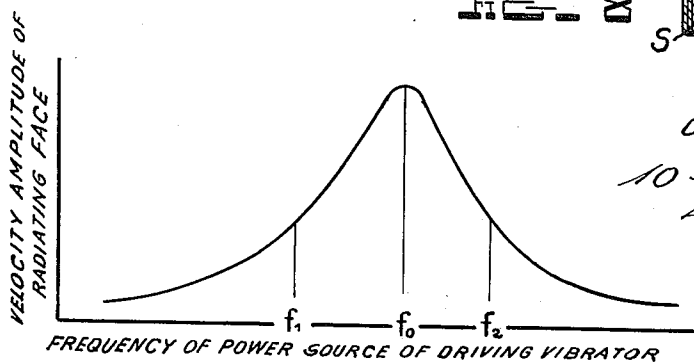
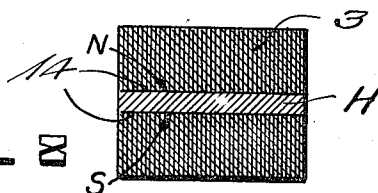
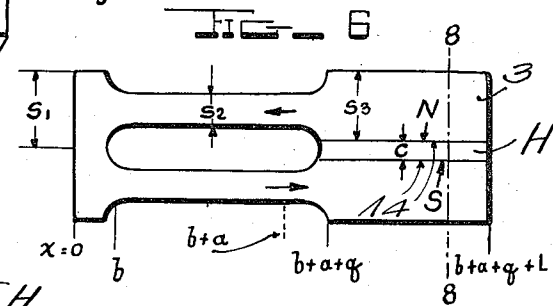
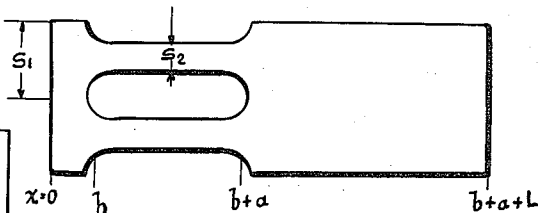
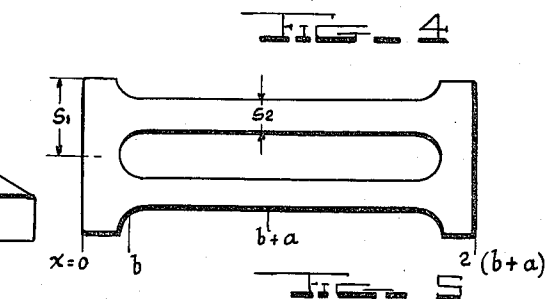
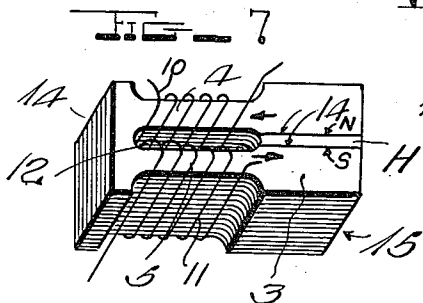
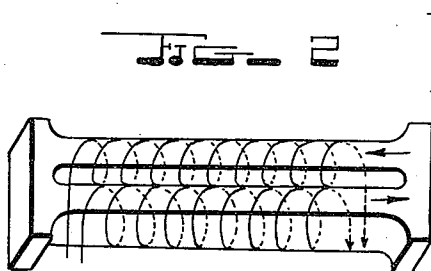
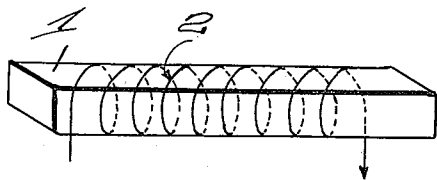
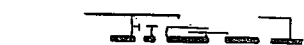
L. W. CAMP

2,550,771

MAGNETOSTRICTION TRANSDUCER

Filed July 20, 1948

2 Sheets-Sheet 1



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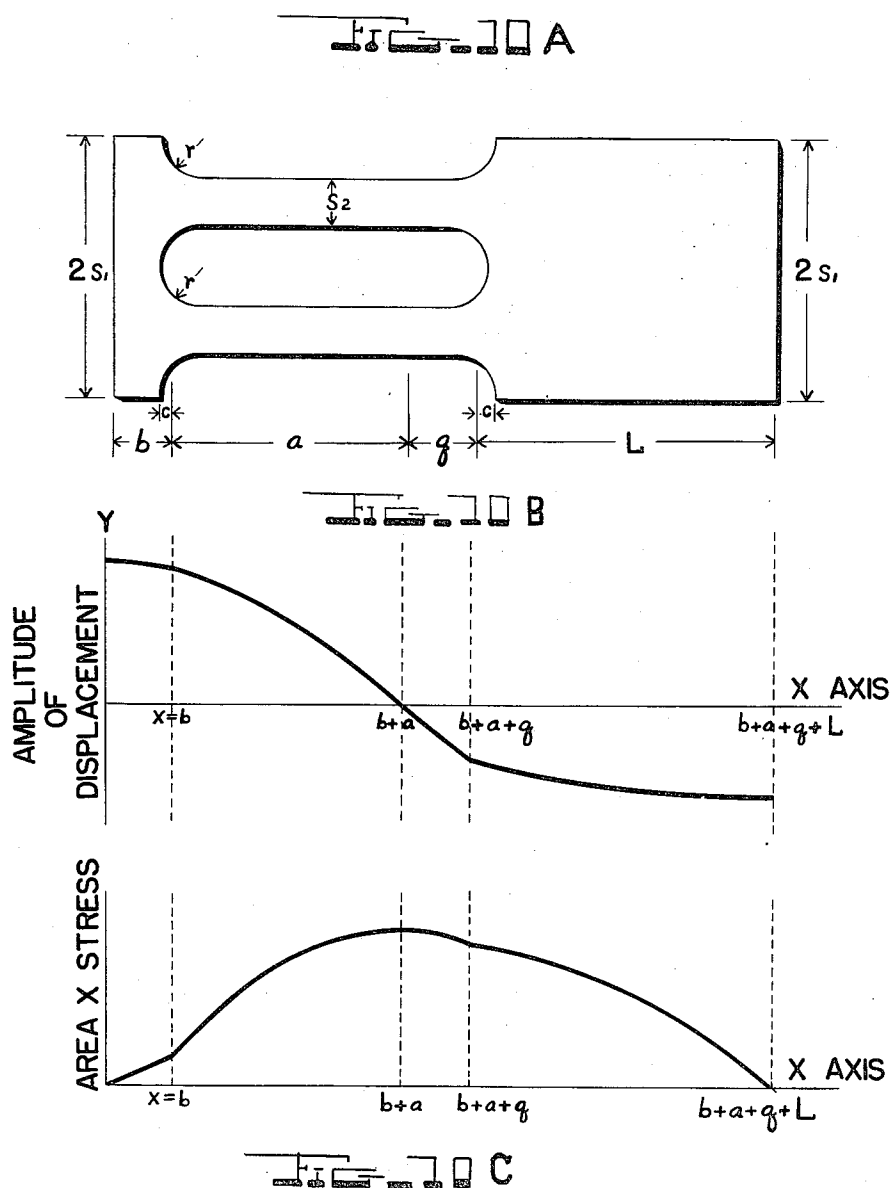
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MAGNETOSTRICTION TRANSDUCER

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2 Sheets-Sheet 2



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MAGNETOSTRICTION TRANSDUCER

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Application July 20, 1948, Serial No. 39,770

5 Claims. (Cl. 171—209)

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My invention relates broadly to electro-acoustic systems and more particularly to an improved method of constructing magnetostriction transducers and to an improved construction of magnetostriction transducer.

One of the objects of my invention is to provide a method of producing magnetostriction transducers by which an increased efficiency is obtained in the production of electro-acoustic energy.

Another object of my invention is to provide an improved design of magnetostriction transducer by which a higher acoustic efficiency is obtainable than has heretofore been possible.

A further object of my invention is to provide a construction of lamination for magnetostriction transducers having a high coefficient of electromechanical coupling for a low "Q" system thereby resulting in higher efficiency of energy conversion.

Still another object of my invention is to provide a construction of lamination for magnetostriction transducers which permits a greater variation in the operating "Q."

A still further object of my invention is to provide a construction of dual purpose magnetostriction vibrator which may be operated at a low "Q" with one end radiating and a high "Q" with the other end radiating for enabling the same die to be used in the stamping of laminations for two entirely different types of vibrators.

Still another object of my invention is to provide a construction of magnetostriction transducer in which the laminations provide very substantial space for the winding coils and allows the coils to be placed in the optimum position for minimum flux leakage while employing a minimum of material and in a stack of minimum weight.

Still another object of my invention is to provide a construction of magnetostriction transducer which is slotted in its more massive section for the insertion of a permanent bar magnet.

Still another object of my invention is to provide a construction of magnetostriction transducer which provides means for magnetically polarizing the laminations thereof or for producing a continuous unidirectional flux through the laminations.

Other and further objects of my invention reside in the production of a magnetostriction transducer with mathematical accuracy on a uniform mass production scale as set forth more fully in the specification hereinafter following

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by reference to the accompanying drawings, in which:

Figure 1 is a theoretical diagram explaining the principles of operation of a magnetostriction bar; Fig. 2 illustrates two magnetostriction bars joined at opposite ends to provide a closed magnetic circuit; Fig. 3 is a curve diagram showing the velocity amplitude of a resonance vibrating system as a function of frequency; Fig. 4 illustrates a magnetostriction lamination symmetrical with respect to both its transverse and longitudinal axes; Fig. 5 illustrates a magnetostriction lamination which is unsymmetrical with respect to its transverse central axis and symmetrical with respect to its longitudinal axis, where the displacement node is located at the junction of the constricted section to the solid block; Fig. 6 shows a magnetostriction lamination which is unsymmetrical with respect to its transverse central axis and symmetrical with respect to its longitudinal axis, where the displacement node is located in the constricted section according to my invention; Fig. 7 is a perspective view of a stack of magnetostriction laminations arranged in a unit and embodying my invention; Fig. 8 is a transverse sectional view taken on the line 8—8 of Fig. 6; Fig. 9 is a diagrammatic and schematic view showing the manner of arranging the windings in electrical and mechanical protective relation to the magnetostriction bars of the vibratile unit; and Fig. 10A shows the relative proportions of the lamination embodying my invention to which I have related the curve diagram of Fig. 10B showing the amplitude of theoretical displacement from rest position of any point along the length of the lamination during the compression part of the cycle; and to which I have related the curve diagram of Fig. 10C showing the distribution of the internal stresses in the material of the lamination illustrated in Fig. 10A.

Fig. 1 illustrates laminated bar 1 of magnetostrictive material with a coil 2 wound about the bar. An alternating current sent through this coil 2 will cause the bar to shorten and elongate with the alternating magnetic flux induced in the bar 1 by the alternating current. If a steady magnetic flux is maintained in the bar 1 by means of a direct current in the coil, or by an arrangement of permanent magnets, and the alternating flux is superimposed on it, the rod will lengthen and shorten with the same frequency as the alternating current.

For the simplest type of motion of the bar of Fig. 1, the center remains fixed and each half moves outward from the center. The distance

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which a point on the bar will move from its rest position increases with the distance of this point from the center. When the driving frequency and the length of the rod have the relation:

$$f = \frac{c}{2L}$$

where f is the frequency, L the length of the rod, and c is the velocity of sound in the rod, there is a resonance phenomenon and the motion of the rod is much greater than at other frequencies. Under these circumstances, the bar is called a half wave vibrator, because the length of the bar corresponds to one half the length of a sound wave in the material at this frequency.

The vibrating system of Fig. 1 has a very poor path for the magnetic flux since half the path's length is in air. This can be remedied by joining two of these bars with end pieces as shown in Fig. 2. When this vibrator is in motion the material in a transverse plane through the bars, equidistant from the ends, remains fixed. The bars are symmetrical with respect to this plane and the two ends of the bars have the same amplitude of motion. If this system is to be used to send out an acoustic signal in one direction, one end is placed in contact with the medium (water in underwater signalling) and the other end is isolated from the medium by an intervening material which will not permit the sound to pass through, sound consisting simply of the vibratory motion imparted to the medium by the vibrating ends of the bars.

A very important matter of concern in the construction of these vibrators used to produce sound in a medium is the efficiency of conversion of the electrical driving energy into the transmitted acoustical energy. For any vibrator, this efficiency is highest at the resonant frequency. According to the previously given relationship

$$f = \frac{c}{2L}$$

for a simple bar, one can choose a proper length for a desired frequency of operation, knowing the velocity of sound in the material used. For the vibrator of Fig. 2 the relationship between frequency and length is somewhat more complicated, but the resonant frequency is still determined by the physical dimensions and the physical properties of the material used. There are a number of different magnetostrictive materials, but the same principles of design are applicable to all of them.

Since these vibrators are to be used in the vicinity of resonance for efficient energy conversion, another very important point is the rate at which the magnitude of maximum velocity of vibration drops off from its peak at the resonant frequency, as the driving frequency varies from the resonant frequency. To make this point clear consider the curve of Fig. 3 which shows how the maximum velocity of the radiating face changes with frequency when the vibrator is being driven by a constant force. The power radiated into the medium is directly proportional to the square of this velocity. If the points f_1 and f_2 represent frequencies at which the vibrator is delivering only one half the power delivered at the maximum, f_0 , then the quantity:

$$\frac{f_0}{f_2 - f_1} = Q$$

defines a quantity generally known as the me-

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chanical "Q" of the vibrator. If this quantity is large, the velocity falls off rapidly away from the resonance frequency, and if small, slowly. The "Q," then, of a transducer is a factor of merit. For most applications, it must be small. The mechanical Q of a magnetostrictive transducer is readily controlled by the lamination design. It is determined by the expression:

$$Q = \frac{\bar{M} W_0}{R}$$

where M is a quantity determined by the dimensions of the lamination, and is called the equivalent mass, $W_0 = 2\pi f_0$, and R is the resistance to motion, internal and external, which absorbs energy from the system. The external resistance is offered by the medium and gives rise to useful energy absorption. The internal resistance leads to a wasteful absorption within the lamination and the bonding material. It can be held to a minimum by a proper design.

The mechanical "Q" of a transducer is, in a sense, a measure of its loading, and, like any other electromechanical device, there is a best load for maximum efficiency. This best load is a function of another very important quantity the coefficient of electromechanical coupling. For magnetostrictive materials, this quantity ranges from 0.1 to 0.3, depending upon the material, its degree of magnetization, and its structural form. If it is desired to operate a transducer at a low "Q," any improvement in the coefficient of electromechanical coupling, increases the efficiency of energy conversion and is an improvement of major importance.

Three types of useful lamination constructions are shown in Figs. 4, 5 and 6. For all of these constructions, the dimension b is limited by a stiffness requirement for the radiating face, and it may well be the same for all of them. In discussing each construction there will be used the convention that

$$S_1/S_2 = m$$

At resonance, the standing wave system for the fundamental form of the construction of Fig. 4 is given by:

$$0 < x < b; y = A \cos kx$$

$$b < x < b + 2a; y = A \frac{\cos kb}{\sin ka} \sin k(b + a - x)$$

$$b + 2a < x < 2(b + a); y = -A \cos k[x - 2(b + a)]$$

where y is the amplitude of displacement from the rest position and $k = 2\pi/\lambda$, λ being the wavelength of sound in the material at the frequency used. The symbol k is a constant for the particular magnetostrictive material used as k is fixed by the properties of the material of the laminations. The equivalent mass of this system per unit area of the radiating surface is given by:

$$\bar{M} = \rho \left(b + a \frac{\sin 2kb}{\sin 2ka} \right)$$

ρ is the density of the magnetostrictive material. For this system M , and therefore "Q" can be varied only by varying the ratio:

$$S_1/S_2 = m = \cot ka \cot kb$$

An increase of this ratio beyond the value 6 is not practical because of the stiffness requirement at the radiating face.

At resonance the standing wave system for the-

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fundamental form of the construction shown in Fig. 5 is given by:

$$0 < x < b; y = A \cos kx$$

$$b < x < b+a; y = A \frac{\cos kb}{\sin ka} \sin k(b+a-x)$$

$$b+a < x < b+a+L; y = A \frac{\sin kb}{\cos ka} \sin k(b+a-x)$$

and its equivalent mass per unit area of radiating surface is given by:

$$\bar{M} = p/2 \left(b+a \frac{\sin 2kb}{\sin 2ka} + L \frac{\sin^2 kb}{\cos^2 ka} \right)$$

For this system, $\bar{M}$ can be varied only by changing the ratio $S_1/S_2 = m = \cot ka \cot kb$. However, for the same value of m , the value of $\bar{M}$ is lower than that for the symmetrical construction of Fig. 4.

At resonance, the standing wave system of Fig. 6 is given by:

$$0 < x < b; y = A \cos kx$$

$$b < x < b+a+q; y = A \frac{\cos kb}{\sin ka} \sin k(b+a-x)$$

$$b+a+q < x < b+a+q+L;$$

$$y = -A \frac{\cos kb \sin kq}{\sin ka \cos kL} \cos k[x - (b+a+q+1)]$$

and its equivalent mass per unit area of radiating surface:

$$\bar{M} = p/2 \left[b + (a+q) \frac{\sin^2 kb}{\sin^2 ka} + L \frac{\sin^2 kb \sin^2 kq}{\sin^2 ka \sin^2 kL} \right]$$

A stack constructed of laminations designed according to these relations is composed of two sections each of which vibrates as would a solid section of a quarter-wave length of sound in the material at the frequency used, though the actual length of the sections is not equal to this quarter-wave length. Such sections are referred to as "equivalent quarter-wave length sections" or the lamination shown in Fig. 6 is said to have a length of two equivalent quarter-wave lengths.

With this system $\bar{M}$ may be varied in three ways: First: by the variation of

$$m = S_1/S_2 = \cot ka \cot kb$$

Second: by the variation of

$$m = S_1/S_2 = \cot kq \cot kL$$

Though this second method appears to be the same as the first, it is quite different. In the expression $m = \cot ka \cot kb$, b is fixed by a stiffness requirement and a is the only variable. But in the practical use of the expression

$$m = \cot kq \cot kL$$

L never becomes small enough to be restricted by this requirement, so that there are two variables in this expression. Third: this lamination may be used with either end as the radiating face—operating with a low "Q" with the less massive end acting as the radiator, and with a high "Q" where the more massive end acts as the radiator. While it appears that the system of Fig. 5 could be used in the same way, it cannot in practice because with its massive end in water, it operates with a "Q" that is too high.

The parallel lines 14 of Fig. 6 indicate a modification of the lamination consisting of a slot of width C cut from this section. Into this slot may be placed a permanent magnet H to provide a constant polarization for the metal. When the

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slot is present, this section is designed according to

$$\cot kq \cot kL = n = S_3/S_2$$

and the expression for $\bar{M}$ must be changed slightly to account for the loss in mass. The polarities for the lamination and the distribution of the magnetic flux through the lamination have been indicated by arrows. The form of polarization shown in Fig. 6 is merely illustrative of one method of effecting polarization.

The construction of Fig. 6 covers any unsymmetrical lamination consisting of two sections as joined at the point $x=b+a$, which point is a displacement node in the vibrator. The one section being designed according to the formula:

$$\cos kb \cos ka = m$$

and the other section designed according to the formula:

$$\cos kq \cos kL = n$$

where m and n may or may not be equal, but $q \pm b$, and $L \pm a$. It will be observed that the design of Fig. 4 requires that both sections be designed alike, while that of Fig. 5 requires that the back section be constructed according to the formula

$$L = \lambda/4$$

My invention covers an infinite number of constructions all having the common characteristic of a displacement node in the constricted section, and an unsymmetrical arrangement of mass about this section.

Fig. 6 shows an embodiment of my invention in which the lamination 3 may be slotted at C to receive the flat magnet H. The laminations are stacked to form the magnetostriction transducer unit represented in perspective view in Fig. 7 where the front face of the stack at 14 and the rear face of the stack at 15 join by the two sections 4 and 5 at opposite sides of the longitudinal slot 12. Windings 10 and 11 are wound on the legs 4 and 5 of the stack as indicated. The polarities and the direction of the magnetic flux have been indicated by arrows. As heretofore noted the slot and the magnetic insert may or may not be included. Fig. 8 is a transverse sectional view on line 8-8 of Fig. 6 and illustrates more particularly the manner in which flat magnet H extends between the rear ends of the laminations 3.

In Fig. 9 I have schematically and diagrammatically shown the manner of protecting the exciting windings 10 and 11 from the sections 4 and 5 of the magnetostriction unit. The windings 10 and 11 are wound upon the constricted sections 4 and 5 but they are protected from contact with the sections 4 and 5 by air-cell rubber pads 6, 7, 8 and 9, which cushion the windings 10 and 11 and prevent contact of the wires with the sharp edges of the stack. The exciting flux is superimposed on the unidirectional polarizing flux provided by the permanent magnetizing device H. The polarities indicated are selected for illustrative purposes only and it will be understood that the polarities may be reversed without adverse effect to the operation.

In Figs. 10A, 10B and 10C I have more clearly illustrated the theory of operation of the magnetostriction unit by illustrating a typical lamination in Fig. 10A with the curves of Figs. 10B and 10C related thereto. The curve of Fig. 10B illustrates the theoretical displacement of any point from a rest position along the length of the lamination during the compression part of a

cycle and progressively along the length of the lamination and with respect to the portions thereof designated in Fig. 10A. In Fig. 10C I have illustrated by a curve diagram the theoretical internal stresses in the material of the lamination corresponding to the conditions of Fig. 10B and the structure of Fig. 10A.

My invention has particular application to underwater sound equipment. A number of the stacks constructed in accordance with my invention may be used to build up arrays having large driving surfaces. It is possible to support these arrays with the stacks directly in the water. Alternately, the stack may be enclosed and have the drawing faces thereof cemented to a rubber diaphragm through which vibrations are propagated or received. My invention also has application wherever vibratory motion is to be produced in any body or fluid.

I have found the magnetostriction unit of my invention highly practical and efficient in operation and while I have described my invention in certain of its preferred embodiments I realize that modifications may be made and I desire it to be understood that no limitations upon my invention are intended other than may be imposed by the scope of the appended claims.

What I claim as new and desire to secure by Letters Patent of the United States is as follows:

1. In a magnetostriction oscillator system, a magnetostriction transducer element comprising a stack of laminations each having a vibratory face portion and a constricted portion connected therewith and constructed according to the equation:

$$\cot kb \cot ka = m$$

in which

k =constant for the properties of the particular material of the laminations= $2\pi/\lambda$

where

λ =wave length of vibration in the material of the lamination

b =length of the vibrating face portion of the laminations

a =length of the constricted portion of the laminations

m =ratio of the cross-sectional area of section b with respect to the cross-sectional area of section a .

2. In a magnetostriction oscillator system, an unsymmetrical magnetostriction transducer element comprising a stack of laminations each having a vibratory face portion and a constricted portion consisting of two sections joined at the point $x=b+a$ where

b =length of the vibrating face portion of the laminations

a =length of the constricted portion of the laminations

x =distance measured from the surface of the forward vibratory face portion along the length of the lamination

3. In a magnetostriction oscillator system including an unsymmetrical magnetostriction transducer element comprising a stack of laminations each consisting of a light vibratory forward face portion, a more massive vibratory rearward end portion and a restricted leg section joining the two end portions, the lamination being designed as two equivalent quarter-wave sections according to the equations

$$\cot kb \cot ka = m = S_1/S_2$$

for the forward quarter-wave section and

$$\cot kq \cot kL = n = S_3/S_2$$

for the rearward quarter-wave section in which k =a constant pertinent to the properties of the material in the laminations

b =length of forward vibrating end portion of the lamination

a =a length of restricted portion adjacent to b

S_1 =width of forward vibrating face portion

S_2 =width of restricted portion

S_3 =width of massive end portion

q =a length of restricted portion adjacent the rearward massive end portion such that $a+q$ =entire length of restricted portion

L =length of rearward section of lamination, whereby the vibrational node for the fundamental mode of vibration is located within the restricted leg section

4. In a magnetostriction oscillator system as set forth in claim 3 in which the magnetostriction transducer element comprises a stack of laminations each of which consists of two or more coplanar sections joined laterally adjacent to each other to form a single unit.

5. A magnetostriction oscillator comprising a magnetostriction element formed by a stack of laminations, each end of said laminations having an acoustically vibratory end face and an adjacent solid end section, a constricted portion extending between said solid end sections, a slot extending longitudinally between said solid end sections and within said constricted portion, the displacement node of the laminations lying in the constricted portion of the stack, one of said end sections having a central slot therein disposed in alignment with the slot in said constricted portion and a flat permanent magnetic member in said last mentioned slot for establishing a unidirectional magnetic field through said laminations.

LEON W. CAMP.

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