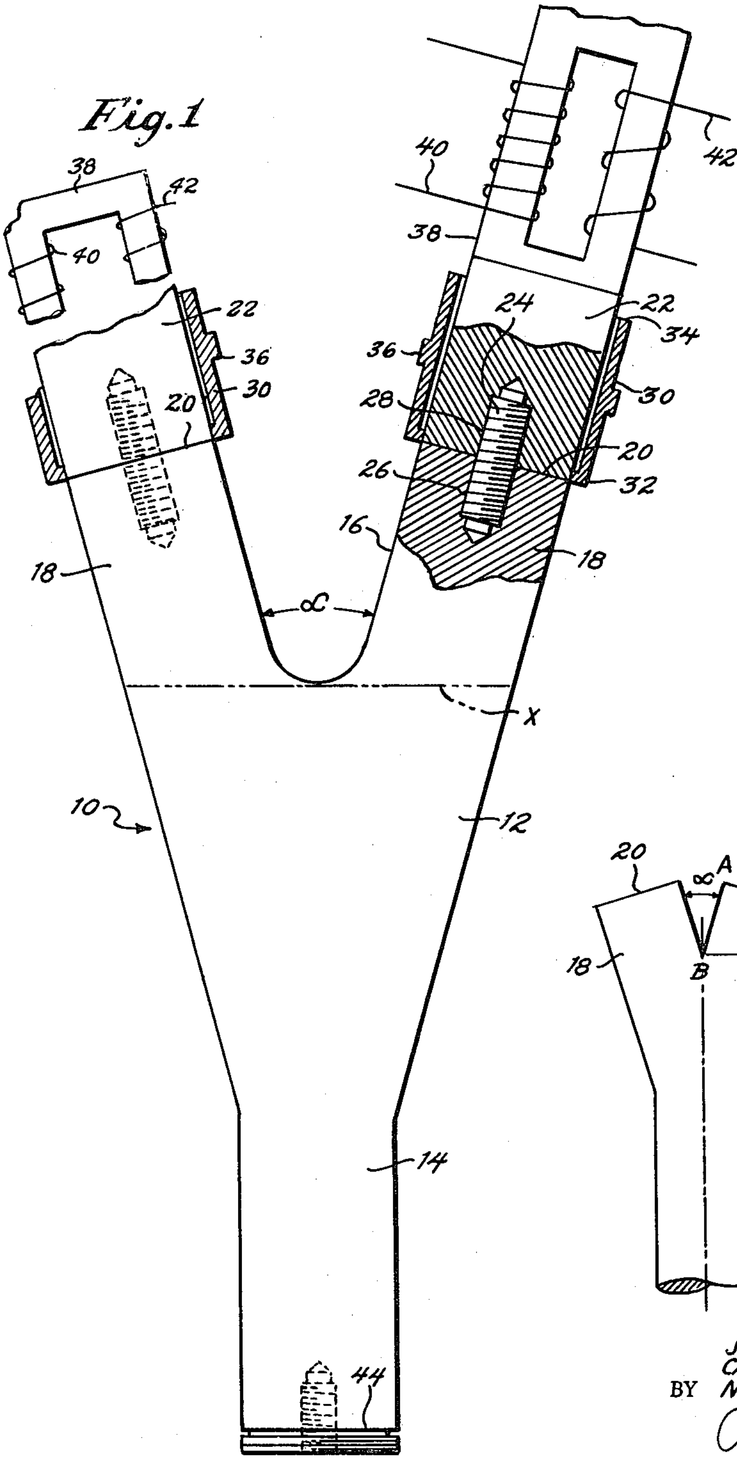
Sept. 8, 1964 J. B. JONES ETAL 3,148,293

VIBRATORY DEVICE FOR DELIVERING VIBRATORY ENERGY AT HIGH POWER

Filed June 5, 1961 2 Sheets-Sheet 1

Fig. 1



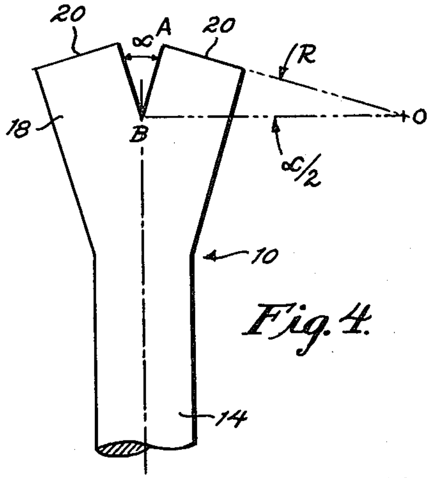


Fig. 4.

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ENERGY AT HIGH POWER

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Fig. 2.

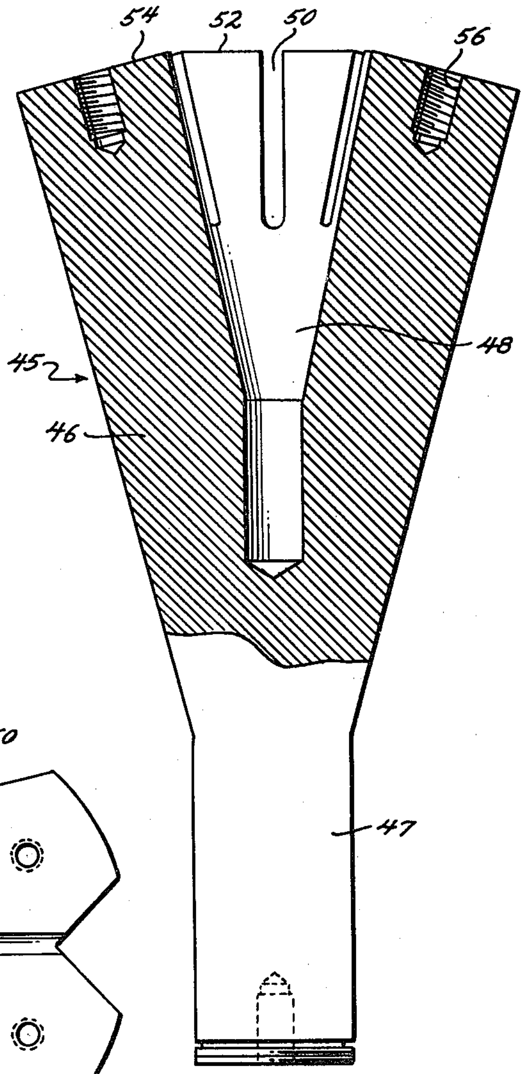
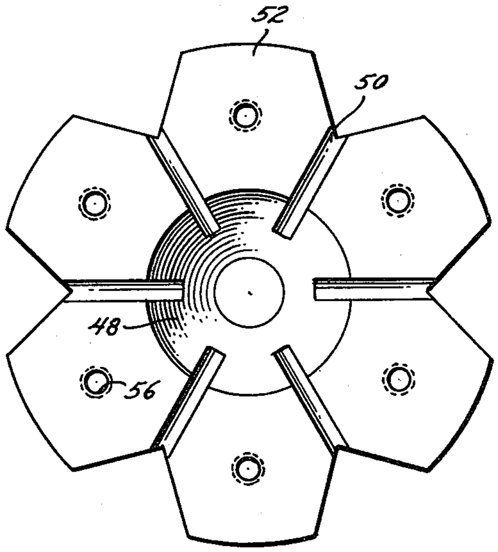


Fig. 3.



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VIBRATORY DEVICE FOR DELIVERING VIBRATORY ENERGY AT HIGH POWER

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8 Claims. (Cl. 310—26)

The present invention relates to vibratory apparatus, and more particularly to high-power apparatus useful for such vibratory applications as ultrasonic extrusion, ultrasonic welding, etc. Specifically, this invention relates to apparatus for increasing available in-phase acoustic power in a single acoustical conductor having a cross-section of fixed dimensions.

Most present day vibratory applications require the production and delivery of relatively small amounts of vibratory energy. The use of high-power instead of low-power apparatus in these applications would be needlessly costly or would be actually detrimental to the end result. However, other applications of vibration will have increased capabilities if transducer-coupling systems are provided which can handle greater amounts of power than are available with conventional systems.

The basic components of vibratory systems for operative applications include: (1) a power supply and driving unit for converting electrical energy to an appropriate frequency for utilization with an electromechanical transducer, (2) an electromechanical transducer, such as a magnetostrictive, electrostrictive, or piezoelectric type transducer for converting the electrical energy to mechanical vibratory energy at said frequency, and (3) a coupler or coupling system designed to operate at the same frequency for conducting the mechanical vibrations from the transducer to the work.

In a transducer, the efficiency of conversion of the electrical driving energy into vibratory (acoustical) energy is greatest at the resonant frequency of the transducer. The resonant frequency of the transducer is primarily determined by the physical dimensions and physical properties of the materials from which it is made. There are well known equations for ascertaining specific dimensions for various geometries intended for operation at any specific frequency of vibration.

In applying said equations to the design and construction of an electromechanical transducer, there are various dimensional restrictions. These restrictions are well known in the art, and information concerning them is available from such sources as the following: Sonics, by T. F. Hueter and R. H. Bolt (Wiley, 1955); Ultrasonic Engineering, by A. E. Crawford (Academic Press, Inc., 1955); and Design of Nickel Magnetostriction Transducers (The International Nickel Company, Inc., 1955).

The dimensions of a transducer cannot exceed certain limits and still operate efficiently. For example, in the case of the well known magnetostrictive-type transducer comprising a stack of thin laminations of nickel, the length of the transducer and each lamination thereof is usually one-half wavelength of sound in the material at the design frequency. If a conventional magnetostrictive transducer is attached to a coupler of the tapered horn type, the width should be approximately one-quarter wavelength or less. If a spaced-lamina-type transducer is used with the terminal load being a liquid, the transducer face can be greater than one-quarter wavelength.

The electrical power input to a magnetostrictive-type transducer at a fixed frequency is essentially a function of the volume of the magnetostrictive material and the load to which energy is being delivered. The acoustic power

output of the transducer is limited by the permissible energy input and by the conversion efficiency of the transducer in converting electrical energy to mechanical energy.

The volume of such a single magnetostrictive transducer cannot be increased indefinitely because as the cross-section increases beyond certain limits, cooling and eddy current shielding problems become progressively more difficult and even insurmountable. Therefore, the energy output to the work area does not increase in direct proportion to the energy input to the transducer.

Design limitations also exist in connection with the electrostrictive and piezoelectric transducers which are often used in ultrasonic systems. Moreover, the coupling member to which the transducer is attached also has dimensional limitations. The coupling member generally has a length of one-half wavelength or an integral multiple of one-half wavelength according to the properties of the materials of construction and the frequency of vibration. There are exceptions, usually determined by the type of work to be performed. However, such a coupling member must be attached across substantially the entire end of the transducer in order to absorb substantially all of the vibratory energy available from the transducer.

If a coupling member cross-section dimension exceeds more than about one-quarter wavelength at the frequency of the sound wave in its material of construction, it will not usually vibrate in the desired mode but will dissipate the energy.

As the ratio of diameter to wavelength increases, vibrating a system of this sort in the longitudinal mode becomes impractical. This is so because the ratio of the phase velocity to the longitudinal velocity drops to such a low value that other modes of vibration predominate.

Therefore, only within limits can increasing the size of the transducer and its associated coupling member accomplish an increase in power delivery. Thus, the problems of generating and transmitting high power levels of vibration are complex and are not subject to ready solution by extrapolation.

In has been discovered that the amount of vibratory energy in a transducer-coupling system can be increased by means of apparatus which comprises a plurality of transducers together with a single coupling member having critical dimensions in addition to the usual resonant length dimensions. Such a coupling member will have a configuration of a tree limb, fan, etc. In this manner, the coupling member will be a compact and complete unit containing no joints between sections of the coupling member involved. Therefore, the coupling member is not likely to suffer from dynamic coupling phenomena which are generally associated with a combination of individually vibrating units in close proximity. Such phenomena are also associated with individually vibrating units whether or not they are joined at some common point. An example of such a combination of individually vibrating units is shown in FIGURE 11 of U.S. Patent 2,806,328.

The present invention provides a distinct and unusual advantage over transducer-coupling systems wherein there is provided a combination of individually vibrating units in close proximity. The most distinct and unusual advantage of the present invention is the ability to handle increased power, within the limits imposed by the above mentioned considerations. Also, the present invention avoids unsatisfactory operation which can lead to complete self-destruction in a vibratory system.

To be effective, the coupling member of the present invention must have continuity over the resonant length. The arms must have a length which does not permit them to be driven in any but the designed frequency vibratory mode. The angle at which the arms couple into the common section must be below the critical value angle, that is, the value beyond which attenuation occurs without a phase change, and preferably below one-half this value. Furthermore, the transition from the arms to the common section should be a smooth curve without any abrupt change; this is facilitated by keeping the aforesaid angle small.

It is an object of the present invention to provide a novel apparatus having substantially large acoustic power handling capacity.

It is another object of the present invention to provide an efficient high-power handling system while still maintaining system dimensions within the known, prescribed and inherent limitations.

It is a further object of the present invention to provide a novel transducer-coupling system enabling two or more transducers to operate in phase into a single load permitting a lower power density per transducer and more ready dissipation of the transducer heat load.

It is yet a further object of the present invention to provide a novel means for improving the impedance matching of transducer-coupling systems.

Other objects will appear hereinafter.

For the purpose of illustrating the invention there is shown in the drawings a form which is presently preferred; it being understood, however, that this invention is not limited to the precise arrangements and instrumentalities shown.

FIGURE 1 is a side elevational view of the coupler of the apparatus of the present invention, with portions shown in section for purposes of clarity.

FIGURE 2 is a side elevational view, partly in section, of a modification of the coupler of the present invention.

FIGURE 3 is an end elevational view of the coupler shown in FIGURE 2.

FIGURE 4 is a partial elevational view of the coupler apparatus illustrated in FIGURE 1.

Referring to the drawing in detail, wherein like numerals indicate like elements, there is shown in FIGURE 1 the coupler of the apparatus of the present invention designated generally as **10**.

The coupler **10** comprises a frusto-conical section **12** and a cylindrical section **14** extending longitudinally from the smaller diameter end of the frusto-conical section **12**. The larger diameter end of the frusto-conical section **12** is provided with a slit **16** which extends longitudinally of the frusto-conical section **12** to form a pair of divergent arms **18**. The end surface **20** of each of the arms **18** is perpendicular to the longitudinal axis of the arms **18**. The straight section **14** and the arms **18** may be rectangular in transverse cross section as well as circular.

The vibratory power handling capacity of metallic materials normally used for coupler members, such as steel, Monel, aluminum bronze, etc., depends upon various properties of the materials, including especially their stress limits. Analysis indicates that the vibratory power handling capacity of such well known materials may reach values as high as 12,000 watts per square centimeter under proper conditions (essentially no standing waves); e.g., when all or essentially all of the energy put in is emitted at the end opposite the transducer. Therefore, it is apparent that the cross-sectional area of the straight section **14** of FIGURE 1 (**47** of FIGURE 2) may well be no larger than the end cross section of the arms **18** of FIGURE 1 (or **54** of FIGURE 2).

The end surface **20** of each of the arms **18** are secured in abutting relation to one end of a separate coupling member **22** by a threaded connector **24**. Connector **24** is threaded at both ends, with one end being threaded in the hole **26** in one arm **18** and the other end being threaded into the hole **28** in the coupler member **22**.

Each of the coupling members **22** (which, in conventional manner have a physical length equal to an integral number of one-half wavelengths of sound at the design

frequency in the material used), are adapted to be supported on a frame by means of the force-insensitive mount **30**. The force-insensitive mount **30** comprises a cylindrical metal shell, such as a cylindrical steel shell, which is resonant according to its material and geometry. The shell of the force-insensitive mount **30** has a length of one-half wavelength according to the metal used at the applied frequency, or a length equal to an integral number of one-half wavelengths.

One end **32** of the force-insensitive mount **30** is metallurgically bonded to the coupling member **22**. The other end **34** of the force-insensitive mount **30** is free from attachment. An annular flange **36** extends radially outwardly from the shell.

The force-insensitive mount **30** is an Elmore mount, which is described in detail in U.S. Patent 2,891,178. Since the end **34** is free from any attachment, a true node will develop in the force-insensitive mount **30** at the flange **36**. Since the force-insensitive mount **30** is well known to those skilled in the art, a more detailed explanation is not considered necessary. Such a support mount is particularly useful in applications requiring the use of force in conjunction with vibration. It is convenient to use in non-force applications also, although it may sometimes be dispensed with in such situations according to the degree of control desirable or necessary.

A magnetostrictive transducer **38** is metallurgically bonded to one end of each of the members **22** or may be bonded directly to face **20**, if intermediate coupler member **22** is not used. Each of the magnetostrictive transducers **38** is of conventional construction and comprises a laminated core of magnetostrictive material properly dimensioned to insure axial resonance with the frequency of the alternating current applied thereto. Each of the magnetostrictive transducers **38** are provided with a polarizing coil **40** and an excitation coil **42**.

The length of the coupler between the end surfaces **20** on the arms **18** and the end surface **44** of the straight portion **14** should approximate an even number of one-quarter wavelengths in the material of the coupler at the applied frequency. The arms **18** preferably, although not necessarily, should be of the same length; any difference in length should be an integral number of wavelengths. However, the arms should be long enough so that the maximum continuous through-distance X is not much more than one-quarter wavelength in the material at the design frequency. It should be especially noted that the angle of separation alpha between the arms **18** is critical and must be below a value at which attenuation occurs without phase change, and preferably below one-half of this value. Maximum power transmission occurs when particle displacement and force are in phase. Changes in phase which accompany attenuation result in changes in power transmission. In connection with a 15 kc. unit made of Monel, the angle alpha was 25 degrees. The length of the slit **16** extending from the end surfaces **20** of the arms of said 15 kc. unit must therefore be less than one-eighth of a wavelength long. If dimensioned in this manner, the arms **18** will not vibrate in any mode except the design frequency vibratory mode.

For example, the angle alpha must be large enough so that the transducers can be properly and easily attached and so that there is a minimum of interaction between the individual transducers and the associated magnetic fields. On the other hand, the angle alpha must be below the aforesaid critical value angle, i.e., the value beyond which attenuation occurs without phase change. However, means have been found for determining the angle alpha so as to satisfy both considerations.

Thus, if the critical angle is α as shown in FIGURE 4, then angle $AOB=\alpha/2$.

Hence,

$$\tan \alpha/2=AB/R \qquad (1)$$

But AB is approximately $\lambda'/8$ where λ' is the wavelength corrected for the coupler cross-sectional area and for curvature. If power transmission through the coupler of the present invention is considered analogous to transmission through a bent rod, then for waves to be transmitted without attenuation:

$$R > \frac{\lambda}{2\pi} \qquad (2)$$

where λ is the uncorrected thin rod wavelength.

See, for example, copending application Serial No. 120,233, entitled Apparatus and Method for Introducing High Levels of Vibratory Energy to a Work Area, and filed June 28, 1961, for discussion of bent rods, which is incorporated herein by reference. Combining (1) and (2) and substituting λ'/8 for AB gives:

$$\tan \alpha/2 < \frac{\lambda'/8}{\lambda/2\pi}$$

Hence:

$$\tan \alpha/2 < \frac{\lambda'\pi}{\lambda 4} \qquad (3)$$

But $\lambda'/\lambda \geq 1$. Hence (3) is satisfied if $\tan \alpha/2 < \pi/4$, or $\alpha < 2 \tan^{-1} \pi/4 = 2 \tan^{-1} 0.785$. Therefore, the critical value of α is $2 \tan^{-1} 0.785 = 76.3$ degrees, and to avoid attenuation this angle must be maintained below this value, and preferably below one-half of this value. As has been said, 25 degrees was found to work very satisfactorily.

It is to be especially noted that the transducers 40 are operating in phase. Accordingly, the system shown in FIGURE 1 will enable the end surface 44 to deliver twice the amount of vibratory energy generated by each of the transducers 40. In order to accomplish this desirable result, the coupler 10 must be constructed in the manner set forth above. The end surface 44 need not be flat but may for example be an annular ring.

Although the coupler 10 of the present invention shown in FIGURE 1 has only two arms for the delivering of vibratory energy from two separate transducers, the coupler may have any desired number of arms uniformly clustered around the large diameter end of the conical section 12 of the coupler 10. If there are only two arms, the configuration can assume a wishbone shape with a solid common section. In this case, the angle alpha is especially critical since the configuration will not have the increased transverse stiffness possible with a circular symmetry, such as that of FIGURES 2 and 3. Referring to FIGURES 2 and 3, there is shown a modification of the coupler of the present invention designated generally as 45, having more than two arms on the conical section.

As shown more clearly in FIGURE 2, coupler 45 comprises a conical section 46 and a straight cylindrical section 46 extending from the smaller diameter end of the conical section 46. The conical section 46 has a conical recess 48 in the center of its larger diameter end. The conical section 46 has six slits 50 across its larger diameter end which extend from the outer surface of the conical section 46 to the recess 48.

The slits 50 are uniformly spaced around the conical recess 48 as shown more clearly in FIGURE 3. All of the slits 50 are of uniform length. All of the slits 50 has a length corresponding to the length of the slit 16, that is one-eighth of a wavelength long according to the properties and construction of the material of the coupler 45. The slits 50 provide the coupler 45 with six arms 52 uniformly spaced around the large diameter end of the conical section 46. The end surface 54 of each of the arms 52 is approximately perpendicular to the longitudinal axis of the arms 52. The end surface 54 of each of the arms 52 is provided with a threaded hole 56 similar to hole 26. A coupling member and a transducer similar to coupling member 22 and transducer 38 is adapted to be mounted against the end surface 54 of each of the arms 52. It is to be noted that brazing rather than mechanical connection by threading, of these elements is possible.

When a separate magnetostrictive transducer is secured in end-end relation to the end surface 54 of each of the arms 52, the coupler 45 will deliver many times the amount of vibratory energy delivered by each of the transducers. In the embodiment shown in FIGURES 2 and 3, each of the transducers will operate in phase.

The present invention can be used for continuous-type operation such as is used in production welding, whether ultrasonic spot-type welding or ultrasonic continuous-seam welding. Thus, a 2000-watt ultrasonic unit with one transducer can be operated at peak power only for short time periods; to permit continuous duty, the transducer (if of the magnetostrictive type) could practically have an input of only about 800 watts (assuming a design resonant frequency of about 15 kc.), and two transducers would be needed to provide the requisite power necessary to satisfactorily weld some materials and material thicknesses on a production basis within the capacity of such a unit. More transducers would be needed to provide still greater power for welding still other materials and material thicknesses with the necessary repetitive quality for production work, assuming, of course, that the same nominal frequency of vibration is used as the design frequency for the various welders.

It will be appreciated that, while the present invention is useful in connection with ultrasonic spot-type welding, as, for example, with the present invention as an intermediate link in the transducer-coupling system, the circular symmetry shown in FIGURES 2 and 3 is particularly adaptable for continuous-seam welding, as shown and described in United States Patent No. 2,946,120, issued July 26, 1960, in the names of James Byron Jones, William C. Elmore, and Carmine F. De Prisco, entitled Seam Vibratory Welding Apparatus and Method. In such use, it is advantageous to couple a subsequent exponentially-tapered resonant coupling member at the point 44 and to couple such member in turn to a resonant disk tip, such as is disclosed in copending United States Patent application Serial No. 747,254, filed July 8, 1958, in the names of William C. Elmore and Carmine F. De Prisco, entitled Vibratory Device, and now Patent No. 3,017,792, in order to effect welding at higher welding rates and with heavier-gage materials than would be otherwise satisfactorily weldable with conventional mono-transducer-coupler systems.

Moreover, the present invention was used, with powers approaching 5000 watts, in an ultrasonic extrusion press, and a substantial increase in extrusion velocity was obtained and a substantial reduction in applied extrusion pressures was enabled.

When constructed in the proper manner, the present invention is potentially capable of delivering two, three, four, etc. times as much power as a single transducer. In constructing a coupler in accordance with the present invention, one starts with the transducer dimensions which are fixed principally by the frequency of operation and the aforesaid limitations. Next, the member 22 is dimensioned so as to be an integral number of one-half wavelengths long and so as to have a material area on one end which matches the material area on the end of the transducer 38. Also, the desired end surface area 44 is ascertained (depending upon the end area of any terminal or near-terminal resonant elements to be attached at 44).

When the area of the end surfaces 20 and 44 have been ascertained, the length of the coupler 10 may be computed from the following equation:

$$\frac{\lambda'}{2} = \frac{c}{\omega}\sqrt{\pi^2 + \ln^2 \frac{d_0}{d_x}}$$

where:

λ' is the corrected wavelength
C=velocity of sound in the coupler material
$\omega=2\pi f$
ln=natural logarithm
f=the required frequency

$$\frac{d_0}{d_x}=\sqrt{\frac{A_0}{A_x}}$$

where d=diameter if cross section is circular, A_0 is area at $l=0$, and A_x is area at $l=x$

$$\frac{\lambda'}{2}$$

is the corrected half wavelength which is the length of the coupler.

It is to be noted that, in determining the length of the coupler **10**, a transformation ratio is involved, which, inasmuch as a change in area is involved from one end of coupler **10** (the end surfaces **20**) to the other end (where it joins straight portion **14**), takes advantage of the well known transformer laws (covering, for example, exponential conical, parabolic conical, configurations) which provide beneficial results in connection with vibratory amplitude and particle velocity, as when areas **20** are larger than the area at the other end, thereby transforming the impedance in an appropriate ratio of input and output areas. The exponential taper laws are particularly desirable in connection with the present invention, since the impedance matching characteristics thereby afforded do not introduce reactive components in this transformation.

When the length of the coupler has been ascertained, it is a simple matter to compute the length of the slit **16**. As pointed out above, the length of the slit and the angle alpha are critical features of the present invention. These features are interrelated in effect with the other features described above, if undesirable mode conversion and resultant inefficient power transmission are to be avoided.

If the transducers used are of the magnetostrictive type, they are preferably removably connected to the arms in the manner as shown in FIGURES 1–3. This makes it easier to wind the coils on the stacks, enables the stacks to be readily replaceable in the event of a malfunction, and facilitates the provision of a cooling apparatus for the stacks.

The coupler of the present invention is usually an intermediate member; however, in connection with a wishbone configuration, for example, it might be a terminal, i.e., work-contacting member. It is designed to be utilized with another coupler member which may be one-half wavelength long and which may or may not be a terminal member adapted to be connected to the surface **44**. In this regard, it should be noted that the coupler of the present invention is adapted to be connected to a plurality of transducers operating in phase. The arms of the coupler of the present invention are connected end to end with the vibration-generating means so that they vibrate axially. Since the transducers are operating in phase, the coupler member of the present invention delivers vibratory energy from end surface **44** in a longitudinal direction.

While the subject invention has been described in connection with an ultrasonic welder, the same array may be used for purposes of ultrasonic extrusion thereby enabling an extension of the ultrasonic extrusion equipment's capabilities in view of the increased power which is rendered available by the coupler of the present invention. For example, the coupler of the present invention could be utilized in an ultrasonic extrusion apparatus of the type set forth in copending application Serial No. 114,836 entitled Ultrasonic Extrusion Apparatus and filed June 5, 1961.

The present invention may be embodied in other specific forms without departing from the spirit or essential attributes thereof and, accordingly, reference should be made to the appended claims, rather than to the foregoing specification as indicating the scope of the invention.

We claim:

1. An acoustical device comprising an acoustical coupling member, said coupling member being adapted for vibration in a longitudinal mode and having a physical length substantially equivalent to an acoustical length of an integral number of one-half wavelengths of sound at substantially a given operating frequency in the material of said member, one end of said member terminating in at least two separate arms, the included angle between said arms being less than about 76 degrees, and the sum of the cross sectional area of the end faces of said arms being at least equal to the area at the end face of said member remote from said arms.

2. In a vibratory device comprising an elongated acoustical coupling member having first and second ends, said acoustical coupling member's first end having a plurality of arms, said acoustical coupling member being for transmitting mechanical vibratory energy substantially in the longitudinal mode of vibration from said arms of said first end to said second end, said acoustical coupling member having a physical length substantially equivalent to an acoustical length of an integral number of one-half wavelengths of sound in the material of said coupling member at the frequency of operation in said longitudinal mode, said acoustical coupling member being constructed so that its largest transverse dimension located below said arms is substantially equivalent to an acoustical dimension not more than about one-quarter wavelength of sound in the material of said coupling member at said frequency, and a plurality of means for providing mechanical vibratory energy to said acoustical coupling member, each of said arms being attached to separate such means, with the means attached to each of said arms being adapted for providing mechanical vibration at substantially the same frequency and in substantially the same phase, with the included angle between any adjacent two of said arms being less than about 76 degrees.

3. In a vibratory device the combination as set forth in claim 2 wherein the material area ratio between the end faces of said arms and the second end of said member is substantially one to one.

4. In a vibratory device the combination as set forth in claim 2 wherein the material area ratio between the end faces of said arms and the second end of said member is greater than one to one, with the lesser value of the ratio being at said second end.

5. In a vibratory device in accordance with claim 2 with said included angle between any adjacent two of said arms being preferably the same angle as that between every other adjacent two of said arms.

6. In a vibratory device the combination of an elongated acoustical coupling member having an upper end and a lower end, said acoustical coupling member's upper end comprising a plurality of arms, said acoustical coupling member being for transmitting mechanical vibratory energy substantially in the longitudinal mode of vibration from said arms of said upper end to said lower end of said acoustical coupling member, said acoustical coupling member having a physical length substantially equivalent to an acoustical length of an integral number of one-half wavelengths of sound in the material of said coupling member at the frequency of operation in said longitudinal mode of vibration, said acoustical coupling member being constructed so that its widest portion located below said arms is substantially equivalent to an acoustical dimension not exceeding more than about one-quarter wavelength of sound in the material of said coupling member at said frequency, and a plurality of means for providing mechanical vibratory energy to said acoustical coupling member, each of said arms being attached to separate such means, with the means attached to each of said arms being adapted for providing mechanical vi-

bration at substantially the same frequency and in substantially the same phase, with the longitudinal axis of each of said arms being displaced from the longitudinal axis of said coupling member below said arms by an angle of less than about 38 degrees, with said angle being preferably the same angle for each of said arms.

7. In a vibratory device comprising an elongated acoustical coupling member having first and second ends, said acoustical coupling member's first end having a plurality of arms, said acoustical coupling member being for transmitting mechanical vibratory energy substantially in the longitudinal mode of vibration from said arms of said first end to said second end, said acoustical coupling member having a physical length substantially equivalent to an acoustical length of an integral number of one-half wavelengths of sound in the material of said coupling member at the frequency of operation in said longitudinal mode, the sum of the cross sectional area of the end faces of said arms being at least equal to the area of the end face of said second end of said member, and a plurality of means for providing mechanical vibratory energy to said acoustical coupling member, each of said arms being attached to separate such means, with the means attached to each of said arms being adapted for providing mechanical vibration at substantially the same frequency and in substantially the same phase, with the included angle between any adjacent two of said arms being less than about 76 degrees.

8. A vibratory device in accordance with claim 6 wherein said angle is about 25 degrees.

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