3,148,293
VIBRATORY DEVICE FOR DELIVERING VIBRA-
TORY ENERGY AT HIGH POWER
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The present invention relates to vibratory apparatus,
and more particularly to high-power apparatus useful for
such vibratory applications as ultrasonic extrusion, ultra-
sonic welding, etc. Specifically, this invention relates to
apparatus for increasing available power and power density
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 undesirably
costly or would be actually detrimental to the end result.
However, other applications of vibration will have in-
creased 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 opera-
tive applications include: (1) a power supply and driv-
ing unit for converting electrical energy to an appropriate
frequency for utilization with an electromechanical trans-
ducer, (2) an electromechanical transducer, such as a
magnetostrictive, electrostrictive, or piezoelectric type
transducer for converting the electrical energy to mechan-
ical vibratory energy at said frequency, and (3) a coupler
or coupling system designed to operate at the same fre-
cquency 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 prop-
eties 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 construc-
tion 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. Haxter and R. H. Bolt (Wiley, 1955); Ultrasonic
Engineering, by A. E. Crawford (Academic Press, Inc.,
1955); and Design of Nickel Magnetostriiction Trans-

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 trans-
ducer 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 pro-
portion 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
dimension 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 prop-
eties 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 sub-
stantially 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
don usually vibrate in the desired mode but will dissipate
the energy.

As the ratio of diameter to wavelength increases, vibrate
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 ac-
complish an increase in power delivery. Thus, the prob-
lems of generating and transmitting high power levels of
vibration are complex and are not subject to ready solu-
tion 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 hav-
ing 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 in-
dividually vibrating units in close proximity. Such phe-
nomena are also associated with individually vibrating
units whether or not they are joined at some common
point. An example of such a combination of individu-
ally 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 ad-
vantage 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 com-
plete 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 loud permitting a lower power density per transducer and more ready dissipation of the transducer heat load.

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

Other objects will appear hereinafter.

For the purpose of illustrating the invention there is shown in FIGURE 1 a side elevational view of the apparatus of the present invention, 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 substantially parallel to the longitudinal axis of the arm 18. The straight section 14 and the arms 18 may be re-entrant 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 (45 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 in the hole 28 in the coupling 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 metallographically 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 insensitivity with vibration or mechanical force application 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 of the coupling member 22. Each of the magnetostrictive transducers 38 is of conventional construction and comprises a luminated 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 integer number of wavelengths. However, the arms should be long enough so that any variation in length is not 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 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 slits 16 extending from the arms 18 might also be one 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 alpha as shown in FIGURE 4, then angle AOB = alpha / 2.

Hence, 

\[ \tan \alpha / 2 = AB / R \]

(1)

But AB is approximately X / 8 where X 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:

$$R > \frac{\lambda}{2\pi}$$  \hspace{1cm} (2)

where $\lambda$ is the uncorrected thin rod wavelength.

See, for example, cupping 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 $\lambda/8$ for $aB$ gives:

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

$$\tan \frac{\alpha}{2} < \frac{\lambda}{\pi}$$  \hspace{1cm} (3)

But $\lambda/\pi$ > 1. Hence (3) is satisfied if $\tan \frac{\alpha}{2} < \pi/\pi$, or $\alpha < 2\tan^{-1} \pi/4 = 2\tan^{-1} 0.785$. Therefore, the critical value of $\alpha$ 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 48 are operating in phase. Accordingly, the system shown in FIGURE 1 will enable the end surface 46 to deliver twice the amount of vibratory energy generated by each of the transducers 48. 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, a conical section can assume a wishbone shape with a solid common section. In this case, the angle alpha is critical since the configuration will not produce 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 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 44 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 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 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 embedment 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 15,500), 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 cupping 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 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 16 may be computed from the following equation:

$$X' = \frac{c}{2\pi} \sqrt{x^2 + \ln \left(\frac{d_1}{d_2}\right)}$$
where:
\( \lambda' \) is the corrected wavelength
\( C_0 = \text{velocity of sound in the coupler material} \)
\( c = \text{frequency} \)
\( \ln = \text{natural logarithm} \)
\( f = \text{the required frequency} \)
\( d = \text{diameter if cross section is circular, } A_b \text{ is area at } l = 0, \text{ and } A_x \text{ is area at } l = x \)

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, a transformation ratio is involved, which, inasmuch as a change in area is involved from one end of the coupler (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 transformer 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 silt 16. As pointed out above, the length of the silt 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 magnetostriuctive 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-
vibration 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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