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Martner

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[45] **Apr. 16, 1974**

[54] **ULTRASONIC GENERATOR AND ATOMIZER APPARATUS AND METHOD**

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[22] Filed: **July 27, 1973**

[21] Appl. No.: **383,331**

[52] **U.S. Cl.**..... **239/4**, 239/102, 259/DIG. 44
[51] **Int. Cl.**..... **B05b 17/04**
[58] **Field of Search**..... 310/8.3, 8.7, 8.2; 239/102, 4; 259/DIG. 44

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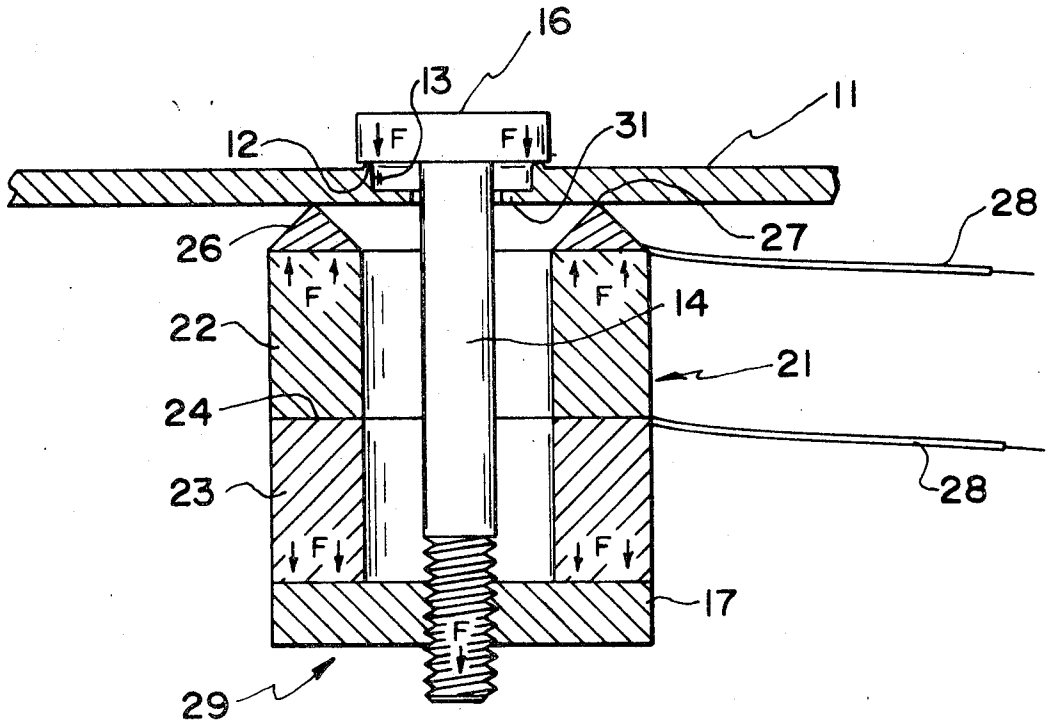
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Primary Examiner—Lloyd L. King
Attorney, Agent, or Firm—Flehr, Hohbach, Test, Albritton & Herbert

[57] **ABSTRACT**

A flexural resonator having predetermined resonant modes is mounted by means of a dynamic clamp which prevents movement of the resonator at the line of clamping. An electrically energized driver urges a member against the resonator exciting the predetermined resonant modes therein. The resonator may be utilized to transmit ultrasonic signals operating, for example, as a predator repellant, or as an atomizer of fluids introduced thereupon. Atomization occurs due to driver displacement amplification in the resonator at the point where fluid is directed onto the resonator surface, whereupon the fluid is thrown off of the resonator surface in small droplet form. Atomized droplet size is a function of the resonator amplitude and frequency.

25 Claims, 13 Drawing Figures



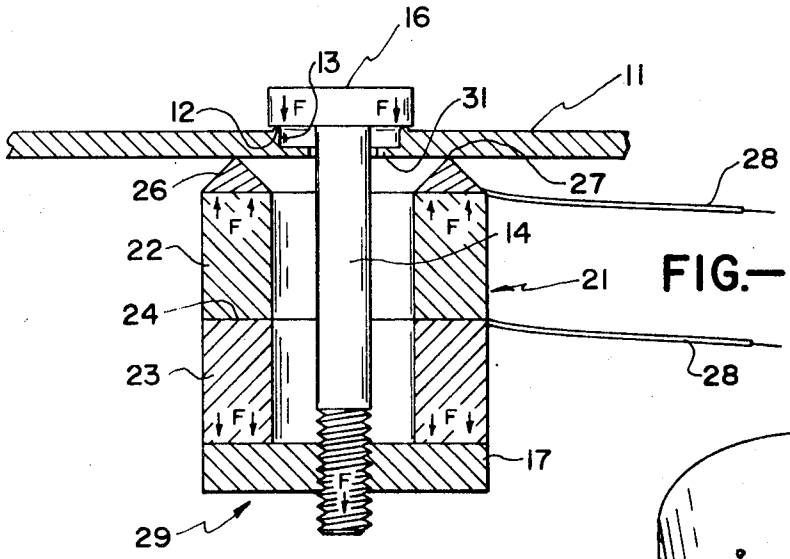


FIG.—1

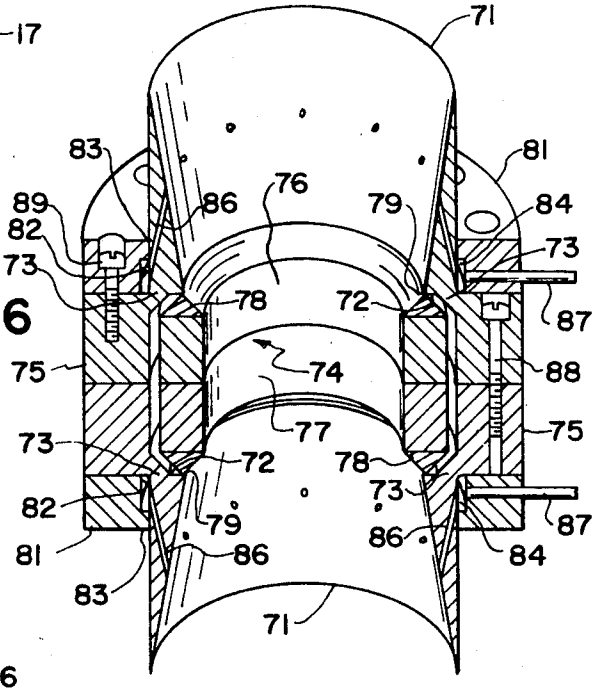


FIG.—6

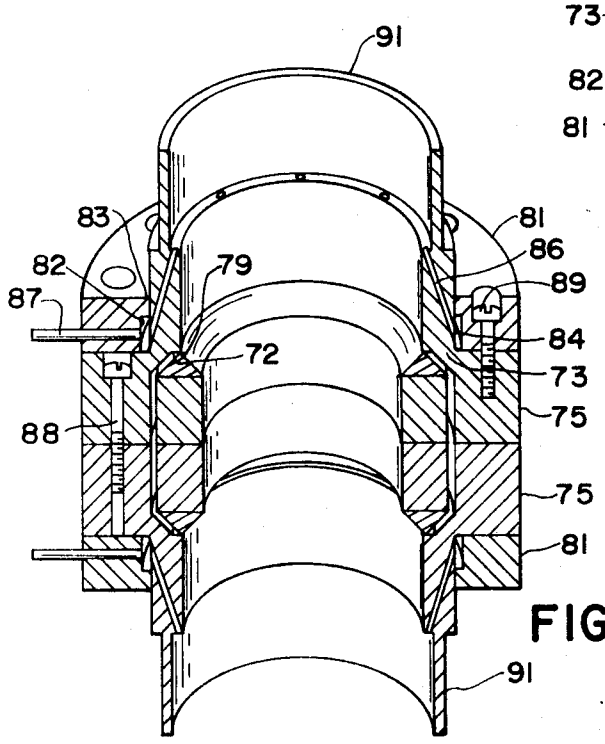


FIG.—7

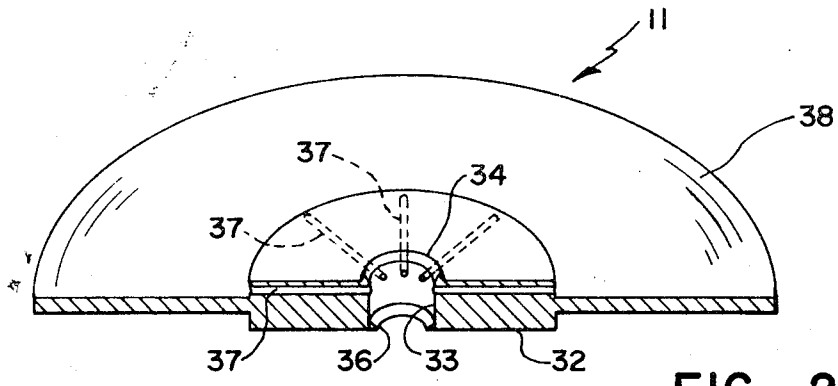


FIG.—2

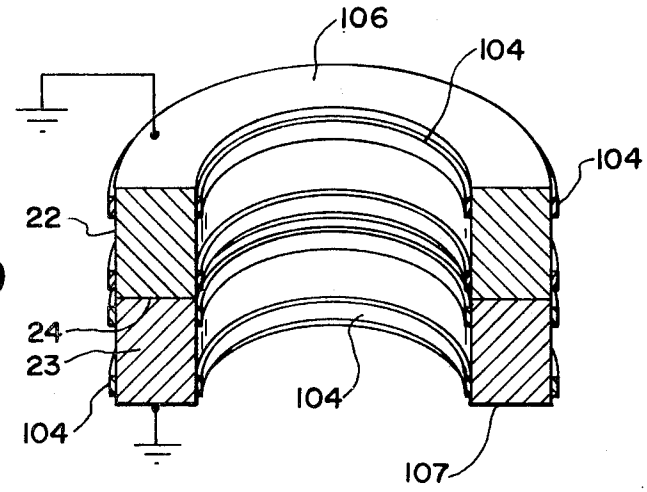


FIG.—9

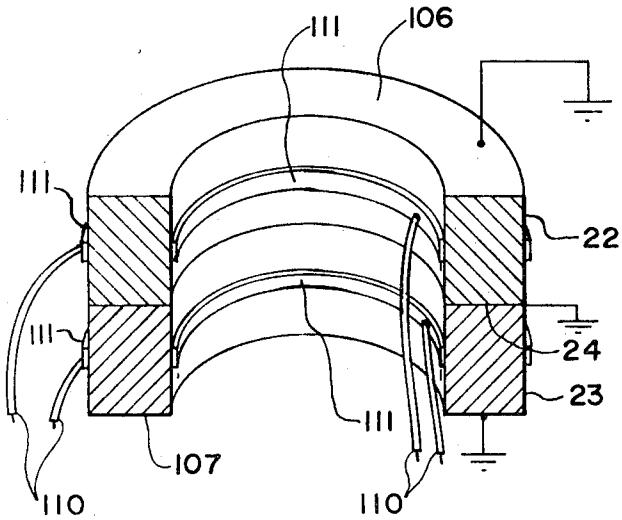


FIG.—11

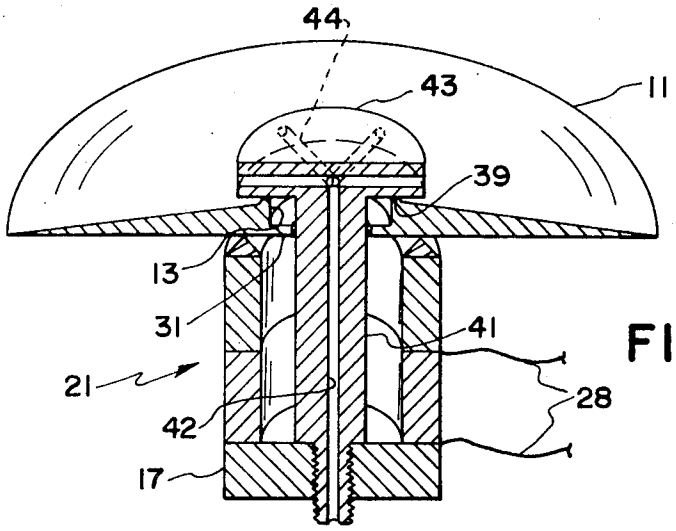


FIG.—3

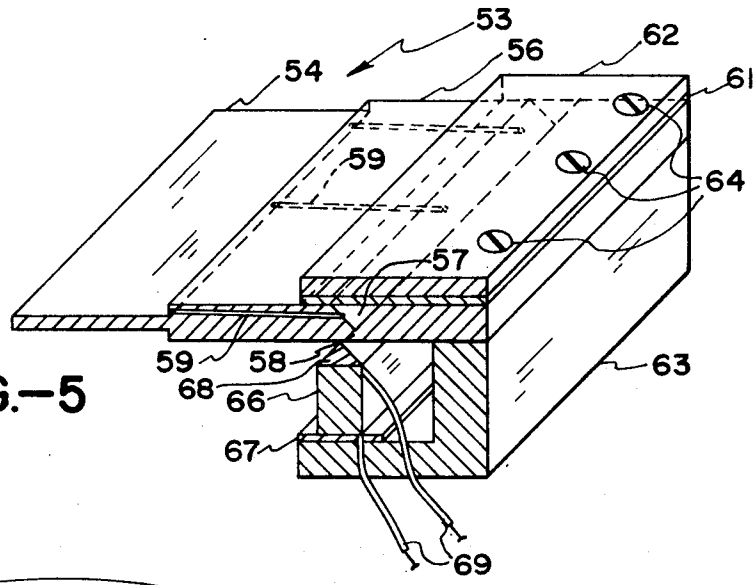


FIG.—5

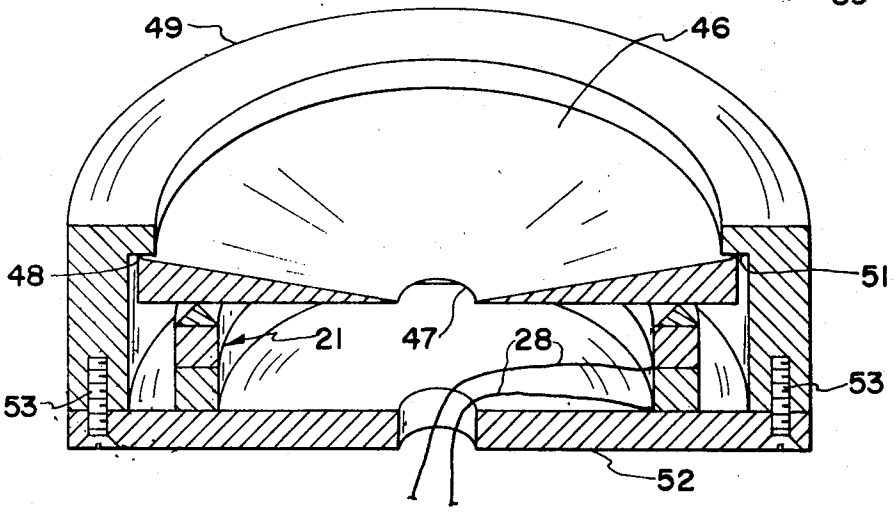


FIG.—4

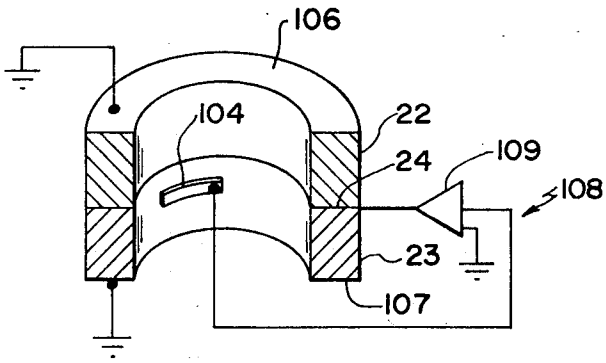


FIG.—10

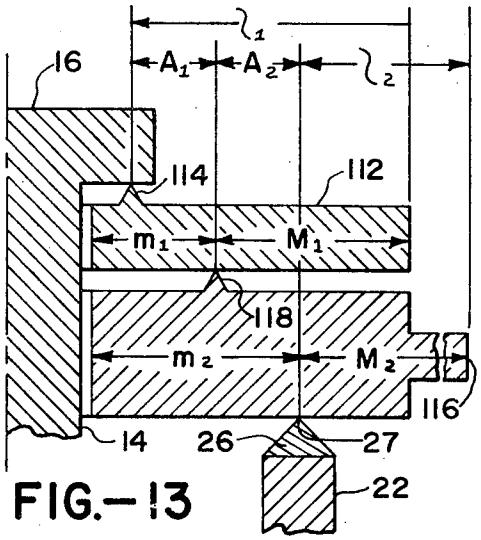


FIG.—13

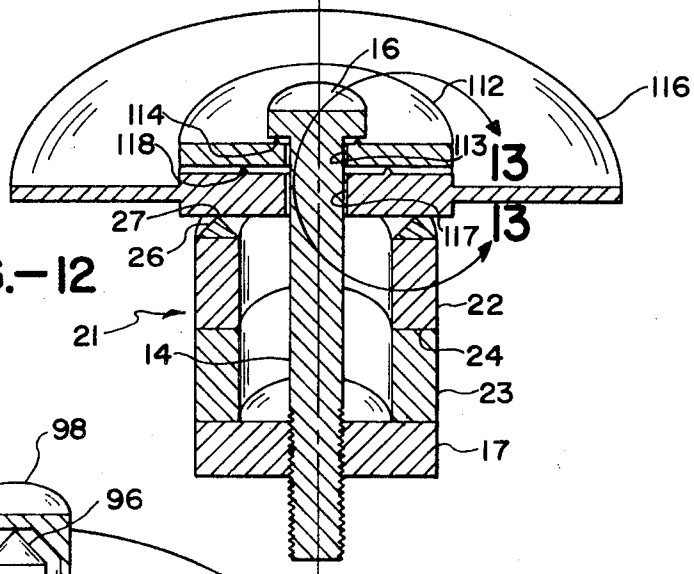


FIG.—12

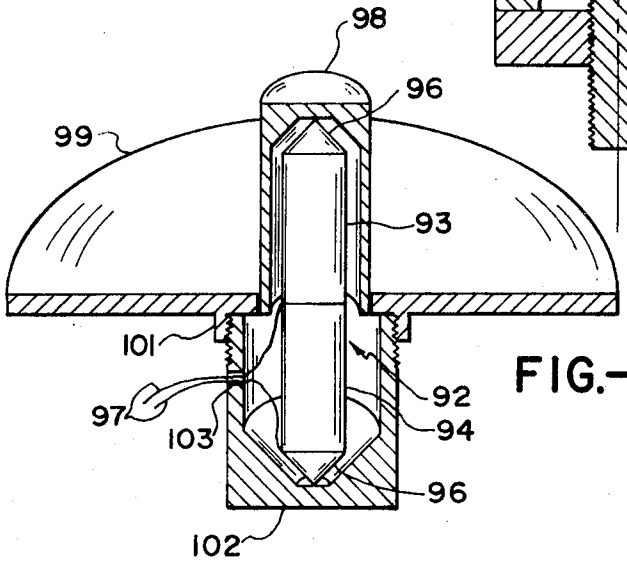


FIG.—8

ULTRASONIC GENERATOR AND ATOMIZER APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

This invention relates to an ultrasonic generator and more particularly to such an ultrasonic generator for use in controlled atomization of fluids.

Study of flexural vibrations of members of various cross section configurations has been an item of interest both theoretically and practically for some time. Due to a general lack of investigative apparatus and analytical techniques, development has been severely limited in the area of designing vibrating systems in frequency ranges higher than those ranges covered by classical equations. In the higher frequency ranges the classical equations provided operating characteristics that departed from predicted design parameters. Therefore attempts to design vibrating systems of the type described herein were relegated entirely to empirical methods.

It was therefore apparent that a new approach, both experimental and theoretical, was necessary. Some preliminary theory was described in an article "Design of High Amplitude Resonators," in Volume 44, J. G. Martner, Journal of the Accoustical Society of America, No. 3, 717-723, Sept., 1968. New knowledge was applied to the design of triangular thin wedges as described in an article "High Frequency Flexural Modes of Straight Wedges," in Volume Su-18, J. G. Martner, IEEE Transactions on Sonics and Ultrasonics, No. 2, 96-103, Apr., 1971. From the base provided by these two works and others it was obvious that means were needed for providing predictable operating characteristics in practical ultrasonic generators for atomizing fluids and projecting ultrasonic energy.

SUMMARY AND OBJECTS OF THE INVENTION

There is provided an ultrasonic generator for atomizing fluids and for projecting ultrasonic energy which includes a transducer for driving a dynamically clamped resonator. Dynamic clamping is attained without undue clamp mass by generating forces at the clamp which are 180° out of phase with respect to the resonator driving forces. The driving force is spaced from the resonator clamp and the driving frequency excites predetermined vibratory modes in the resonator. This provides resonator displacement amplitude amplification as compared with the driver displacement amplitude. A resultant ultrasonic wave projection is produced and a fluid may be directed to impinge upon the resonator surface for atomization whereby droplets are provided having a size determined by the frequency and resonator displacement amplitude.

In general it is an object of the present invention to provide an ultrasonic generator for projecting an ultrasonic energy wave having a predetermined frequency.

Another object of the present invention is to provide an ultrasonic generator for atmoizing a fluid impinging on the resonator at predetermined rates of flow and for providing a predetermined median atomized droplet size.

Another object of the present invention is to provide an ultrasonic generator for underwater communications.

Another object of the present invention is to provide an ultrasonic generator for atomizing fuel for use in internal combustion engines.

Another object of the present invention is to provide an ultrasonic generator for emulsifying fluids mixtures.

Another object of the present invention is to provide an ultrasonic generator with controlled predominating vibratory modes.

Additional objects and features of the present invention will appear from the following description in which the preferred embodiments are set forth in detail in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional view of a disc type of ultrasonic generator showing the primary components.

FIG. 2 is an isometric sectional view of a stepped horn disc type resonator showing fluid flow passages.

FIG. 3 is an isometric sectional view showing an ultrasonic generator of the disc type with fluid conveying passages.

FIG. 4 is an isometric sectional view of an ultrasonic generator of the disc type having peripheral dynamic clamping.

FIG. 5 is an isometric sectional view showing an ultrasonic generator of the cantilevered flat plate type.

FIG. 6 is an isometric sectional view showing an ultrasonic generator of the tubular type.

FIG. 7 is an isometric sectional view showing an additional configuration of the tubular type generator.

FIG. 8 is an isometric sectional view of a disc type ultrasonic generator having an isolated driving means.

FIG. 9 is an isometric sectional view of a driver showing frequency mode control electrodes applied.

FIG. 10 is a combination isometric sectional view and schematic diagram showing a circuit for enhancing a specified vibratory mode.

FIG. 11 is an isometric sectional view of a driver showing frequency doubling with auxiliary electrodes applied.

FIG. 12 is an isometric sectional view of a stacked resonator.

FIG. 13 is a detail view showing the driving and clamping points for the stacked resonator of FIG. 12.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The resonators may take the form of circular or rectangular plates having a free edge or they may be in the shape of tubes having a free end. The cross section of the plates or tube walls are fabricated in varying shapes which determine the resonant frequency, the degree of amplitude amplification, and the mode of vibration in the resonator.

FIG. 1 shows one embodiment of the invention including a resonator, driving system, and dynamic clamp wherein a resonant plate 11 is of annular configuration. As will become apparent, the resonator 11 has a slightly raised portion 12 immediately surrounding a centrally located counter bore 13. A center post 14 passes through the centrally located counter bore 13 and has an integral head or flange 16 at one end which contacts the raised portion 12 on plate 11. The other end of center post 14 threadibly engages a base plate 17. A cylindrical electromechanical transducer 21 in-

cludes half portions 22 and 23 which are bonded together on a common plane 24. A protective drive member 26 is bonded to the top side of transducer half portion 22. The driver member 26 is triangular in cross section, and contacts the underside of resonator 11 along a line 27 spaced from the line of contact between the raised portion 12 and flange 16. A pair of electrical leads 28 are provided, one of which is connected to the bond on common plane 24 and the other of which is connected to the electrically common side of transducer half portions 22 and 23.

The center post 14 and base plate 17 form a dynamic clamp shown generally at 29. The manner in which dynamic clamping is obtained is as follows. Transducer 21 is assembled by bonding transducer half portions 22 and 23 together at plane 24, bonding protective drive member 26 to the top surface of transducer half portion 22, and connecting electrical leads 28 as shown in FIG. 1. The assembled transducer 21 is placed on the top surface of base plate 17 and the resonator disc 11 is plated atop protective drive member 26. Center post 14 is lowered through the counter bore 13 in disc 11 for threaded engagement with base plate 17. Flange 16 is turned until transducer 21 is placed in compression resulting in center post 14 being placed in tension. An alternating voltage impressed across leads 28 alternately expands and contracts transducer half portions 22 and 23 within the elastic deformation range of the transducer material. The driving forces generated by the expansion and contraction are directed through protective drive member 26 to the resonator 11 along line 27. When the upper face of transducer half portion 22 expands upwardly the lower face of transducer half portion 23 expands downwardly a like distance. Thus, any tendency for the force applied at line 27 to push the raised portion 12 upwardly is counteracted by a force exerted downwardly through center post 14. The line of contact between raised portion 12 and flange 16 is prevented from moving in this manner.

A flange 31 projects into the bottom of the counter bore 13 in resonator 11 and has an inside diameter closely fitting the diameter of center post 14. Flange 31 acts to maintain resonator disc 11 in a centered position relative to center post 14. The raised portion 12 provides a pivot line for resonator disc 11 which cannot move.

FIG. 2 shows a resonator disc 11 having a stepped cross sectional configuration. A thickened center portion 32 has a centrally located counter bore 33 similar to the counter bore 13 in FIG. 1. A raised portion 34 surrounds counter bore 33 on the upper surface of the thickened portion 32. A small flange 36 which may be triangular in cross section serves to center resonator disc 11 much as the flange 31 in the configuration of FIG. 1. The flange 36 is also adapted to support a seal (not shown) about a center post (not shown). A chamber defined by the seal and the walls of counter bore 33 form a chamber. Passages 37 extend radially through thickened portion 32 and provide communication between the chamber and an upper surface 38 of the disc 11.

The resonators 11 in FIGS. 1 and 2 may be used to project ultrasonic energy through any medium in which they are disposed. Alternatively, when they contain passages 37 as in FIG. 2, fluid may be introduced into the central chamber formed by the wall of the counter bore 33 and the flange 36. Fluid so introduced flows through passages 37 to be discharged upon the surface 38. When resonator disc 11 is excited in its resonant vibratory mode, fluid on the surface 38 is thrown off orthogonally from the surface in a mist of fine droplets.

FIG. 3 shows another embodiment similar to that of FIG. 1 but having a resonator disc 11 with a traingular or wedge shaped cross section. The embodiment of FIG. 3 has a transducer 21, a base plate 17, and electrical leads 28 much as the embodiment of FIG. 1. FIG. 3 also shows a raised portion 39 serving the same purpose as the raised portion 12 in FIG. 1. Raised portion 39 need not be as pronounced as raised portion 12 due to the fact that the cross sectional configuration of resonator disc 11 slopes downwardly from the edge of centrally located counter bore 13 toward the edge of disc 11. Centering flange 31 is also present at the bottom of counter bore 13 and a center post 41 has a center bore 42 extending axially into a head or flange 43. Center post 41 is configured to threadably engage disc plate 17. A plurality of passages 44 are provided in communication with center bore 42 passing radially through the flange 43.

A fluid to be atomized is directed upwardly through center bore 42 to pass radially through passages 44 from which it is discharged onto the upper surface of resonator disc 11. As described above, when an alternating voltage is impressed across electrical leads 28 resonator disc 11 is excited in its resonant vibratory mode whereupon it immediately atomizes the fluid into a cloud of microscopic droplets which are thrown off perpendicularly from the upper surface of disc 11.

Another embodiment of the ultrasonic generator for atomizing fluids and for projecting ultrasonic energy is shown in FIG. 4. A resonating disc 46 has a centrally located through hole 47. Around the periphery of the disc 46 on the upper surface is a slightly raised portion 48 serving the same purpose as the raised portion 12 in FIG. 1. It should be noted that the raised portion 48 need only be slight, if it exists at all, because of the downward slope of the upper surface of resonator disc 46. An annular framework 49 has an upper internal flange 51 which contacts the raised portion 48 on resonator disc 46. The bottom of resonator disc 46 is contacted by the transducer assembly 21 as described above which is supported by a base plate 52. The base plate 52 is fastened to the bottom of the annular framework 49 by suitable means such as screws 53. Electrical leads 28 are connected to the transducer assembly 21 as described before.

When an alternating voltage is applied to the transducer through leads 28 in FIG. 4, transducer assembly 21 drives resonator disc 46 into its resonant mode of vibration. The raised portion 48 on disc 46 is clamped tightly against the underside of internal flange 51. As in the embodiments described above, annular framework 49, internal flange 51, and base plate 52 are configured to place the transducer assembly 21 in compression and to maintain that compression throughout the resonating modes of the disc 46. Ultrasonic vibrations may be transmitted from resonator disc 46 through the medium in which the ultrasonic generator of FIG. 4 is situated, or fluid may be discharged upon the surface of resonator disc 46 for atomization as described above. It should be noted that centrally located hole 47 is present only when design so dictates. The

disc 46 may be a solid disc if the desired resonant modes are obtainable thereby.

Still another embodiment of the ultrasonic generator is shown in FIG. 5. A resonator 53 has a stepped configuration with a broad flat resonating surface 54 near the free end, and a thicker section 56 near the clamped end. Thicker section 56 has a "V" shaped groove 57 near the clamped end creating a thin section 58 along the length of thicker section 56. A plurality of passages 59 extends from the "V" shaped groove 57 through the thicker section 56 toward the broad surface 54 near the free end of the resonator 53. A sealing strip 61 overlies the "V" shaped groove 57 near the clamped end of the resonator 53. A backup plate 62 overlies the sealing strip 61. An "L" shaped base member 63 is provided for supporting resonator 53. The backup plate 62 is secured to the base member 63 by suitable means such as screws 64. A transducer 66 of a material which undergoes an elastic deformation in the presence of an electric field is mounted on an insulating strip 67 which is supported by base member 63. A protective drive member 68 is positioned atop transducer 66, having a triangular cross section as described before, with the apex of the triangle contacting the bottom of resonator plate 53 along a line horizontally spaced from the thin section 58. A pair of electrical leads 69 are connected to the opposite ends of transducer 66.

The operation of the ultrasonic generator in FIG. 5 involves the application of an electrical potential across leads 64 for driving the resonator 53. Fluid is introduced into the "V" groove 57 either through the ends of groove 57 or through an inlet pipe (not shown), and subsequently passes outwardly through passages 59 to be discharged upon the broad surface 54 near the free end of resonator 53. The fluid impinging upon the vibrating surface 54 will be atomized as described above. Alternatively, the ultrasonic generator may be used to project ultrasonic energy through the medium in which it is situated. It should be noted that in the embodiment of FIG. 5, as in those embodiments previously described, the base member 63 together with that of plate 62 and screws 64 is configured to place a compressive force across transducer 66. Insulating strip 67 is present in this configuration because only a single section of transducer 66 is used instead of the two half portions 22 and 23 of FIG. 1. Insulating strip 67 prevents electrical potential between leads 69 from being short circuited by the metal dynamic clamp parts, base member 63, backup plate 62, and screws 64.

FIG. 6 shows an embodiment of the present invention in a tubular form. A pair of upper and lower tubular sections 71 having walls with a triangular or wedge shaped cross section are formed with a free end at the apex of the triangle or wedge and a base 72 at the opposite end. A thin section 73 connects the base 72 with an annular flange 75. A transducer assembly 74 has two annular sections 76 and 77 which are bonded together at one end surface. Transducer protective members 78 are bonded to the remaining exposed ends of transducer section 76 and 77. Transducer protective members 78 are triangular in cross section and contact base 72 of the tubular resonators 71 along a line 79 around the base. Collars 81 are formed to fit around the outside of the tubular resonators 71 to rest on flanges 75. A groove 82 is cut in the collar 81 leaving a flange 83 on one end of the inside diameter of collars 81. Chambers 84 are formed between the flange 83, the wall of the groove 82, flange 75, and the outside diameter of tubular resonators 71. A plurality of passages 86 are in communication with the chambers 84 extending with the free end of resonators 71, and emerging through the inner wall thereof. Collars 81 have an inlet pipe 87 extending radially from the outside diameter of the collars 81 in communication with the chambers 84. Flanges 75 are held together by means of screws 88 which threadably engage flanges 75. Collars 81 are secured to flanges 75 by means of screws 89 which also threadably engage flange 75.

The ultrasonic generator of FIG. 6 is excited by an alternating voltage as described above. A stream of air may be passed through the center of the resonator tube 71 for entraining fluids atomized through impingement thereupon. Fluid may be introduced upon the resonating surface of resonating tube 71 by directing it from a fluid source through inlet pipes 87, chambers 84, and the plurality of passages 86 to be discharged near the free end of the resonators 71. Identical resonators are provided mounted back to back, for purposes of mechanical impedance matching, and to provide the dynamic clamping. The component parts are configured to place the transducer assembly 74 in compression when screws 88 are assembled to fasten flanges 75 together. Thin sections 73 are thereby held against linear displacement by the opposing driving forces which drive the upper and lower tubular resonators 71.

The ultrasonic generator of FIG. 6 may also be designed so that the annular transducer assembly 74 has a larger radius than that shown. The transducer 74 drives the resonator 71 by contacting base 72 near the periphery of base 72. The flanges 75, in turn, are made with a smaller radius and located radially inward from the line of contact 79 with transducer assembly 74. The radial locations of thin section 73 and base 72 are reversed to accommodate positioning of the line of contact 79 radially outward from thin section 73. Similarly, collars 81 and screws 89 are thus positioned radially inward of the tubular section 71. The orientation of tubular sections 71 and passages 86 are also reversed without impediment to the designed vibration modes of sections 71. This configuration has as its purpose prevention of direct contact of a passing gas or atomized liquid with electrically energized parts of the transducer assembly 74.

FIG. 7 shows an embodiment much the same as the embodiment shown in FIG. 6. FIG. 7 is present to show a different cross sectional configuration for a tubular resonator 91. The tubular resonators 91 in FIG. 7 are of a stepped cross sectional configuration. The remainder of the assembly in FIG. 7 is identical to that shown in FIG. 6 and like numbers apply to like parts for performing like functions.

FIG. 8 shows yet another embodiment of the ultrasonic generator for atomizing fluids and projecting ultrasonic energy. A transducer 92 of a material which is elastically deformed in the presence of an electric field is utilized. Sections 93 and 94 are bonded together and the remaining free surfaces of transducer sections 93 and 94 have conical transducer protective drive members 96 bonded thereto. An insulated electrical lead 97 is connected to the central bond between transducer sections 93 and 94 and a separate lead 97 is connected to the sides mounting conical protective members 96. A cap 98 is securely fastened, for example by welding, to a disc shaped resonator 99. Resonator 99 has a de-

pending circular flange **101** having internal threads. A lower cap **102** has an open end and external threads adjacent to the open end for mating with the internal thread on depending flange **101.** Leads **97** are brought through a pressure seal **103** in the side of lower cap **102.**

The embodiment of FIG. **8** is especially useful in explosive or flamable environments. The lower cap **102** is screwed into the depending flange **101** so as to cause the transducer assembly **92** to be in compression at all times as described above. Electrical potentials on the surface of the transducer assembly **92** are isolated from the flammable environment in communication with the disc shaped resonator **99.** A flammable fluid may therefore be discharged upon the surface of the disc chaped resonator **99** for atomization upon contact with the resonating surface without danger of inadvertent ignition due to sparks from potential discharge.

Referring to FIG. **9** a view of a pair of annular transducer sections is shown. Upper and lower sections **22** and **23,** as in FIG. **1,** are shown bonded together at a common surface **24.** Auxiliary electrodes **104** are shown deposited on the internal and external surfaces of the transducer sections **22** and **23** for controlling signals generated piezoelectrically on the external surfaces of transducer half.portions **22** and **23.** The transducer material is orientated so that material expansion and contraction takes place in a direction parallel to the cylindrical axis of annular sections **22** and **23.** The open surface **106** on transducer section **22** and **107** on transducer section **23** are at electrical common or ground potential. The bonded surfaces **24** receive the other side of the voltage potential impressed across the transducer **21.**

It is necessary in some ultrasonic generator designs which contain natural vibration modes too close together in frequency, to suppress one or more of the undesirable modes. Local surface voltages having level and phase related to vibration modes are generated on the cylindrical sides of the transducers. To suppress a mode, auxiliary electrodes **104,** whose position and size are determined experimentally, are deposited on the cylindrical sides of transducer halves **22** and **23.** These auxiliary electrodes may be connected either to one another or to ground, depending on the signal phasing and levels generated thereon. The local surface voltage related to an undesirable mode is either connected to ground or to another similarly located electrode where a similar voltage level exists but of opposite phase or polarity. This connection causes radical alteration of the internal electric fields necessary to generate a given mode of vibration within the transducer body thus suppressing the undesirable mode.

There also exists the possibility that a very desirable vibration mode might be very weak and in need of being enhanced. The internally generated fields are enhanced by injecting in phase signals at experimentally determined locations on the surfaces of transducers **22** and **23.** This localized field enhancement causes a weak mode to become strong and particularly useful. The in phase signals are obtained from the electronic amplifier or oscillator whichever is being used to drive the resonator itself. The in phase signals are connected to the auxiliary electrodes.

Referring to FIG. **10,** a view of a similar pair of annular transducer sections **22** and **23** is shown where an auxiliary electrode **104** is used as part of a feedback loop **108** containing an amplifier and oscillator **109.** In some designs it becomes difficult to match the frequency of the oscillator to the natural resonance of the transducer and resonator system. Purely electronic means exist to achieve this matching. However, for the case of resonators of the type described, considerable frequency shifting occurs due to temporary loading of the resonator surface by a liquid layer being atomized. This liquid layer effectively loads the vibrating system with extra mass and causes the system to resonate at a lower frequency. It is part of the invention to provide means by which the oscillator and resonator systems are continually matched in frequency. This is done with the use of a feedback electrode as shown in FIG. **10.** A small electrode **104** deposited on an experimentally determined location on the sides of the transducer assembly containing transducer halves **22** and **23,** picks up the surface signals induced by the internally generated electric fields. The surface signals are connected to the input of the oscillator at **109.** This constitutes a feedback loop for controlling the oscillator output frequency which is amplified at **109** and connected back to the common plane **24** between transducer halves **22** and **23.** Therafter, any change in resonator loading causes a change in resonant frequency which, by means of the feedback loop is transmitted to the oscillator at **109** which changes frequency to maintain the desired driving frequency to maintain the design resonator frequency.

In FIG. **11** there is described yet another arrangement of auxiliary electrodes which provides for the creation of high frequency resonant modes by "electrical division" of a continuous transducer crystal. It may become necessary to design an atomizer producing very small aerosol droplets, as for example those which would be needed in an air purifier or humidifier application. Such apparatus requires median water droplets of approximately 5 micron diameters entrained in an air stream. The vibration frequencies necessary to generate this median droplet size is in excess of 500 Khz. Transducer sections for driving resonators at such high frequencies are necessarily very small and thin with vibration amplitudes so small as to be impractical and inefficient in such an application. To general a high frequency resonant mode with a large transducer it becomes necessary to divide the transducer "electrically" into small vibrating portions by the addition of deposited electrodes **111** on the cylindrical sides of transducer halves **22** and **23.** The electrical connections which provide for a high frequency system using large transducer halves **22** and **23** are as follows. With the upper and lower faces **106** and **107** connected to ground, the common plane interface **24** must also be connected to ground. The driving output of the oscillator-amplifier apparatus **109** in FIG. **10** is connected to the centrally located auxiliary electrodes **111** of FIG. **11.** Four such electrodes **11** are shown and all must be connected together to the driving output of the electrical energy source **109.** This embodiment provides a driving frequency from the transducer which is substantially double that of the transducer pair **22** and **23** connected as shown in FIG. **10** for example.

An embodiment is disclosed where a plurality of electrodes **111** are deposited on the cylindrical sides of each transducer half **22** and **23.** A plurality of additional electrodes (not shown) are deposited between electrodes **111** so that there are equal distances be-

tween electrodes 111 and faces 106 or 107 and between electrodes 111 and the additional electrodes. Using the explanation associated with the doubled frequency configuration above it is clear that a frequency is obtained which is a multiple of the frequency obtained when the transducer pair is connected as in FIG. 10. The multiple is the equivalent of the number of electrodes 111 on one cylindrical side of each transducer half plus one.

Polarization of the transducer halves 22 and 23 is such that the motion of the surfaces 106 and 107 are 180° out of phase. It may be seen that a single transducer such as transducer half 22 may have electrodes 111 deposited thereon. With face 106 and the face in plane 24 connected to ground potential and the power supply connected to electrode 111 on transducer 22, the transducer driving frequency is doubled as described above for the transducer pair, but with only one half the amplitude of course.

By way of example of this arrangement, a pair of annular transducer halves 22 and 23 one-quarter inch thick were bonded together and connected as in FIG. 9 providing a resonant frequency of 248 Khz. Subsequently, centrally located auxilliary electrodes were deposited and connected as shown in FIG. 11. Resonant frequency was observed as 496 Khz. The resulting vibrational mode was strong and capable of driving an annular resonator 11 of the type shown in FIG. 1 at 496 Khz. The resulting atomizing rate experimentally obtained was 168 milliliters per minute of 6 micron median size water droplets, and the amplifier power required to drive the system was 24.7 watts. This arrangement produced an ultrasonic atomizer for use in a practical air purifier.

The electrodes 111 of FIG. 11 may be used separately or in conjunction with the electrodes 104 of FIG. 9, for simultaneously suppressing unwanted vibrational modes and enhancing and maintaining those modes which are desirable. Either piezoelectrical or electrostrictive materials may be used for the transducer 21 described above.

Referring to FIG. 12 a sectional view of an embodiment including stacked resonators is shown. The dynamic clamp and the driver components are identical to those described in FIG. 1 and are given like numbers. An upper resonator 112 has a central hole 113 having a raised portion 114 surrounding the upper edge. A lower resonator 116 also has a centrally located hole 117 and a circular raised portion 118 on the upper surface of resonator 116 with a larger diameter than the raised portion 114. The line of contact 27 is on a greater diameter than the raised portion 118. When the ultrasonic generator with stacked resonators is assembled a raised portion 114 is in contact with the underside of the flanged head 16 on the center post 14. The raised portion 118 on resonator 116 is in contact with the underside of upper resonator 112. As described above, dynamic clamping is obtained at the raised portion 114, and greater amplitudes along the length of lower resonator 116 are attainable due to the translational displacement occurring at the raised portion 118 on lower resonator 116.

The purpose of stacked resonators is to provide a large vibration amplitude over a large surface to gain a greater fluid volume of atomization per unit time. To obtain the advantages promised by this configuration of the invention reference is made to FIG. 13. The condition for balanced resonance in a stacked resonator embodiment is:

$$A_1 m_1 l_1 M_1 = A_2 m_2 l_2 M_2$$

In the above relationship m_1 represents the mass of the upper resonator 112 on one side of the fulcrum represented by raised portions 118 as indicated in FIG. 13. M_1 is equivalent to the mass of the upper resonator 112 on the opposite side of the fulcrum represented by raised portion 118. m_2 is the mass of that portion of the lower resonator 116 on one side of the line of contact 27, and M_2 represents the mass of resonator 116 on the opposite side of line of contact 27 as shown again in FIG. 13. The distance A_1 is the radial distance between the raised portion 114 and the raised portion 118. The distance A_2 is the radial distance between the raised portion 118 and the line of contact 27. The distance l_1 is the radial distance from the raised portion 114 to the outer edge of the upper resonator 112. The distance l_2 is the radial distance from the line of contact 27 to the outer edge of the lower resonator 116.

The concept of the dynamic clamp, as disclosed herein, is that device which prevents a moving or vibrating cantilevered piece from displacing the clamping point or line in any direction. It is difficult to achieve absolute clamping with a static clamp since the mass of the clamp must be considerably larger than that of the vibrating system to prevent movement of the clamping line by the inertial forces generated in the vibrating system. To circumvent the use of large masses in the clamp while still achieving the required clamping stability, the inertial forces generated within the system supplement, or wholly substitute for the mass of the clamp. The generated forces are transferred through the clamping structure to the desired point for applying forces opposing the driving forces tending to move the clamping line. This is a common characteristic in all of the embodiments described. The path for the transmission of the opposing forces to the clamping line is purposely kept to a length less than one quarter wave length of the driving frequency in the medium from which the clamp is made. This design consideration keeps the opposing forces and the driving forces reasonably close to a 180° phase relationship. Referring to FIG. 1 it may be seen that neglecting phase lag in either the driving force or the opposing force, an equal and opposite force would arrive at the clamping line on the raised portion 12 at the same time. As described before the upper face of transducer section 22 expands due to an applied electrical field at the same time that the lower face of transducer section 23 expands downwardly. The downward force is transmitted through the base plate 17 and center post 14 and flange 16 to the clamping line 12. The upward force is transmitted through the protective member 26 and the resonator 11 to the clamping point 12. In this manner, dynamic clamping is attained and the clamping line 12 is held substantially motionless. The dynamic clamping derived from compressive forces within the transducer is necessary to the proper control of the vibratory mode in flexure in any of the resonators described herein.

Due to the complexity of the physical phenomenon involved in the mechanical application of high frequency vibration modes of finite solids, a set of equations has been developed which are capable of solution with the aid of digital computer equipment. Certain of the factors contained in the equations are obtained em-

pirically. Examples of these empirical factors are those related to mechanical coupling with gaseous media when the ultrasonic generator is used to project ultrasonic vibrations, and mechanical coupling with a liquid media of varying layer thickness when the ultrasonic generator is utilized as an atomizer. Cross sectional shape and inclusion of channels within the resonators to carry liquids to points of maximum vibration amplitude also affect the vibratory modes of the resonators. By way of illustration of the method used to arrive at a cross sectional shape for a resonator with predictable vibratory modes which may be driven at ultrasonic frequencies (20 to 2000 Khz), the following is set forth for disc shaped type resonators such as that shown in FIG. 2.

The design of a resonator of the disc type must start by considering the classical differential equations of the transverse displacements w at any point on the disc. The displacement w is given by:

$$D\nabla^4 w + \rho\, \delta^2 w/\delta t = 0 \qquad (a)$$

In the above relationship d is the flexural rigidity of the plate material and is determined from the following relationship:

$$D = Eh^3/12(1-\sigma^2)\mu \qquad (b)$$

In the relationship for flexural rigidity the symbols are identified as follows:

E = Young's Modulus

h = plate thickness

μ = mass density per unit area = $\rho\, h$

σ = Poisson's ratio

(dispersive property of vibration velocity in plates.)

In equation (a) above:

$$\nabla^4 = \nabla^2 \cdot \nabla^2$$

where ∇^2 is the Laplacian operator expressed in polar coordinates as follows:

$$\nabla^2 = \delta^2/\delta r^2 + 1/r + 1/r^2\, \delta^2/\delta\Theta^2$$

In the last expression r is the radius and Θ is the direction angle. Assuming free vibration, the displacement is:

$$w = W \cos \omega t$$

where ω is the circular frequency and W is a function of the position coordinates.

Combining the above equations (a) and (b):

$$(\nabla^4 - \mu\omega^2/D)\, W = 0$$

$$(\nabla^2 + \sqrt{\mu\omega^2/D})\,(\nabla^2 - \sqrt{\mu\omega^2/D})\, W = 0 \qquad (c)$$

The latter equation has a solution by superimposing solutions to the equations:

$$\nabla^2 W_1 + K^2 W_1 = 0$$

$$\nabla^2 W_2 - K^2 W_2 = 0 \qquad (d)$$

where $K^4 = \mu\omega^2/D$

If the vibrating disc is partially or totally immersed in an elastic medium, such as a gas, which is assumed massless as might be the case when a thin layer of liquid is on one surface of the resonator just prior to being atomized, the equation (a) becomes:

$$D\nabla^4 w + Kw + \mu\, \delta^2 w/\delta t^2 = 0 \qquad (e)$$

K in the latter equation is the stiffness of the medium measured in units of force per length unit of deflection per unit area of contact.

The following relationships have as their purpose to find an equation that relates vibration frequency to resonator dimensions and the properties of the resonator material. When vibrating a plate or parts of a plate, twisting and bending moments are related to the displacement w by:

$$M_r = -D\,[\,\delta^2 w/\delta r^2 + \sigma(1/r\,\delta w/\delta r + 1/r^2\,\delta^2 w/\delta\theta^2)\,]$$

$$M_\theta = -D\,[1/r\delta w/\delta r + 1/r^2\,\delta^2 w/\delta\theta^2 + \sigma\,\delta w/\delta\theta]$$

$$M_{r\theta} = -D\,[\,(1-\sigma)\,\delta/\delta r\,(1/r\,\delta w/\delta\theta)\,] \qquad (f)$$

Transverse shearing forces must also be considered which may be represented by:

$$Q_r = -D\,\delta/\delta r\,(\nabla^2 w)$$

$$Q_\theta = -D\,1/r\,\delta/\delta\theta\,(\nabla^2 w) \qquad (g)$$

The edge reactions are:

$$V_r = Q_r + 1/r\,\delta M_{r\theta}/\delta_\theta$$

$$V_\theta = Q_\theta + \delta M_{r\theta}/\delta r \qquad (h)$$

The strain energy of twisting and bending is in polar form:

$$U = \frac{D}{2}\int_A \left(\frac{\delta^2 w}{\delta r^2} + \frac{1}{r}\frac{\delta w}{\delta r} + \frac{1}{r^2}\frac{\delta^2 w}{\delta\theta^2}\right)^2 - 2(1-\sigma)$$

$$\left\{\frac{\delta^2 w}{\delta r^2}\left(\frac{1}{r}\frac{\delta w}{\delta r} + \frac{1}{r^2}\frac{\delta^2 w}{\delta\theta^2}\right) - \left[\frac{\delta}{\delta r}\left(\frac{1}{r}\frac{\delta w}{\delta\theta}\right)\right]^2\right\} r dr d\theta \qquad (i)$$

The above system of equations is solved assuming Fourier components in Θ providing the following:

$$W_{(r,\theta)} = \sum_{n=0}^{\infty} W_n(r)\cos n\theta + \sum_{n=0}^{\infty} W_n^*(r)\sin n\theta \qquad (j)$$

In the latter relationship n is the number of nodal diameters for a particular mode of resonance. Substituting equation (j) into equation (d) one obtains:

$$d^2W_{n1}/dr^2 + 1/r\,dW_n/dr - (n^2/r^2 - K^2)W_{n1} = 0$$

$$d^2W_{n2}/dr^2 + 1/r\,dW_{n2}/dr + (n^2r^2 - K^2)W_{n2} = 0 \text{ Here: } K = \sqrt{\mu\omega^2/D} \qquad (k)$$

An identical relationship exists for W_n^*. These equations (k) are forms of Bessel's equation with the solution:

$$W_{n1} = A_n J_n(Kr) + B_n Y_n(Kr)$$

$$W_{n2} = C_n I_n(Kr) + D_n Y_n(Kr) \qquad (e)$$

In the Bessel equations J_n, Y_n, are first and second kind of Bessel functions and I_n, K_n are modified Bessel functions of the first and second kind. The terms A_n through D_n determine the mode shape and are obtained from the boundary conditions of the particular resonator type.

The general solution to equation (c) above is:

$$W_{(r,\theta)} = \sum_{n=0}^{\infty} \left[A_n J_n(Kr) + B_n Y_n(Kr) + C_n I_n(Kr) + D_n K_n(Kr) \right] \cos n\theta + \sum_{n=0}^{\infty} \left[A_n^* J_n(Kr) + B_n^* Y_n(Kr) + C_n^* I_n(Kr) + D_n^* K_n(Kr) \right] \sin n\theta \quad (n)$$

The equations (a) through (m) are general equations and are known relationships. In order to design useful resonators one must first determine the proper boundary conditions applicable to the particular design, introduce these boundary conditions into the proper equations above, solve the equations and thus determine the proper frequency parameters λ that are used in the frequency equations for a particular shape resonator. The equations (a) to (m) above are especially applicable to disc shaped atomizer resonators. To apply these equations to plate or tubular type resonators it becomes convenient to change the coordinate system from polar to either orthogonal, skew, or some other suitable system depending on whether the atomizer is rectangular, tubular, or some other shape.

By way of example, the design of a resonator of a disc type is undertaken which is assumed to be free to vibrate at the periphery and having a radius a. The boundary conditions are:

$$M_4(a) = 0$$
$$V_r(a) = 0 \quad (A)$$

These latter two relationships are valid since the bending moment M_r and the edge reaction V_r are zero. Using equations (f), (g) and (h) it can be shown that the boundary conditions for M_r and V_r give the following frequency equation:

$$\lambda^2 J_n(\lambda) + (1-\sigma)\,[\lambda j_n'(\lambda) - n^2 J_n(\lambda)]/\lambda^2 I_n(\lambda) - (1-\sigma)\,[\lambda I_n'(\lambda) - n^2 I_n(\lambda)] = \lambda^3 I_n'(\lambda) + (1-\sigma)n^2\,[\lambda J_n'(\lambda) - J_n(\lambda)]/\lambda^3 I_n'(\lambda) - (1-\sigma)n^2\,[\lambda I_n'(\lambda) - I_n(\lambda)] \quad (B)$$

The roots of this last equation are located between the zeros of the function $J_n'(\lambda)$ and $J_n(\lambda)$ and larger roots may be calculated from the series:

$$\lambda = \gamma - m\,;\ 1/8\gamma - 4(7m^2+22m+11)/3(8\delta)^3 - \ldots \quad (C)$$

where $m = 4n^2$ & $\gamma = \pi/2\,(n+2s)$

Values of λ^2 which are the frequency parameters being sought, have been computed in Volume 24, Coldwell et al, Phil. Mag., ser. 7, No. 165, page 1041 (1937), and are presented in Table form. Once the values for the parameter λ^2 are found, they are used to determine the physical dimensions of a desired resonator and applied to the specific equation for the resonator type. In this instance:

$$\lambda^2 = \omega a^2 \sqrt{\mu/D} \text{ where } f = \omega/2\pi \quad (D)$$

ω is the circular frequency
μ is the usual mass density per unit area
D is the flexural rigidity of the resonator.

Solving the relationship (D) for the frequency f which is desired, design parameters for a given resonator are obtained.

Since some of the resonators disclosed herein are annular shaped discs the center hole radius is designated b. The following reference contains λ^2 values for this type of resonator which may be used as a first approximation for a specific design; Volume 14, Raju, P.N., Journal of the Aeronautical Society of India, No. 2, page 37 (1962). Modifications are required to account for the mode of driving, the desired local vibration amplitude distribution, the location of nodal lines, and the inclusion of liquid flow passages and support points.

By way of further application of the above equations the following is set forth. Assume the design of an atomizer is desired which is centrally clamped and which must vibrate at a resonant frequency of 62 kilohertz. The selection of this frequency is for the purpose of producing an atomized fluid with droplet sizes centering on 15 microns. First a determination of the frequency parameter λ^2 for the shape desired is undertaken. The shape here will be that of a circular disc of uniform cross section that must contain a hole in the center to provide for the proper driving system which will be similar to that shown in FIG. 1. The frequency parameter λ^2 is determined from proper solutions to equations (a) through (m) which are modified by the suitable boundary conditions. A computer program has been devised that allows determination of eigen solutions for different nodal configurations. The radius of the centrally located hole is represented by the symbol "b" and that of the outer rim by the symbol "a". The disc thickness is represented by "h" and the number of nodal diameters by "n". The number of nodal circles is represented by "s". The following frequency parameters are obtained for various combinations of n and s. A logical design dimension ratio of $b/a = 0.3$ was chosen. It can be shown that the corresponding frequency parameters λ^2 for given values of n and s are:

$$n = 0,\ s = 1:\ \lambda_{01}^2 = 31.6$$
$$n = 2,\ s = 1:\ \lambda_{21}^2 = 43.0$$
$$n = 3,\ s = 1:\ \lambda_{31}^2 = 56.7$$

Assuming a central hole radius to be 0.79 centimeter, the outer rim radius becomes 2.64 centimeters. The equation for an annular type resonator free at the rim and clamped at the inner rim is:

$$f_{ij} = h\lambda_{ij}^2/4\pi\ \sqrt{3\,a^2}\ \sqrt{E/\rho(1-\sigma^2)} \quad (D)$$

Where: σ is Poisson's ratio and $\sigma = 0.33$ for aluminum.

The resonator material is assumed to be aluminum having a Young's modulus "E" of 6.98×10^{11} dynes per square centimeter, and h, the disc thickness, is chosen as 0.4 centimeters. Where the symbols i and j are values of n and s respectively, thus providing different values for λ^2, substitution in the frequency equation provides the following results:

$f_{01} = 45.27$ Khz

$f_{21} = 61.60$ Khz

$f_{31} = 81.23$ Khz

From the above it is seen that the value of f_{21} approaches the design frequency of 62 Khz. This provides a disc which will vibrate with two nodal diameters and one nodal circle, is fabricated from aluminum, and has the above dimensions. This resonator is clamped in the manner described in FIG. 1 showing the transducer bonded to the base plate member **17** which provides the dynamic clamp that is part of this invention.

A typical driving system for the invention disclosed herein of the type shown in FIG. 1 might have the following dimensions by way of example. The transducer assembly **21** may be 1 inch long by 1 inch in diameter. The center post **14** may be 0.3 inches in diameter and the flange **16** may be 0.8 inches in diameter. The center post **14** may be 2 inches long. When the system is assembled it is tightened across the transducer **21** just sufficiently to provide a compressed assembly so that upon vibrating the transducer is never allowed to reach an uncompressed state where it would chatter against the underside of the resonator **11**.

As may be seen by the above design analysis for an annular disc resonator the mode f_{01} is 45.27 Khz and provides the largest vibration amplitude. To effectively suppress this mode it becomes necessary to paint a set of shorting electrodes on the surface of the transducer. The location and the size of the electrodes are determined experimentally from a rigorous surface motion plot which is done with a suitable vibration pickup apparatus.

In the above example an atomizer was produced with an actual resonant frequency of 59.1 Khz with a rate of atomization of 185 cubic centimeters of water per minute. The power consumption of the transducer was 18.2 watts and a feedback loop such as that at **108** containing a two transistor amplifier such as that at **109** in FIG. **10** was used for controlling the desired driving frequency.

An ultrasonic generator for use in atomizing fluids and for projecting ultrasonic energy through a medium has been devised having a low mass dynamic clamp, allowing resonant mode control, and providing a method for designing resonators with predictable operating characteristics.

I claim:

1. An ultrasonic generator of the type energized from an electrical energy source comprising a resonator, transducer means connected to said electrical energy source and responsive to electrical energy to expand and contract, said transducer means including means for engaging said resonator along a line of contact spaced from one edge of the resonator, and clamping means for engaging said one edge and said transducer means to clamp said transducer means between said resonator and said clamp whereby a predetermined vibration mode is induced in said resonator when said transducer means is energized producing a displacement amplitude in said resonator which is an amplification of the displacement amplitude of said transducer means.

2. An ultrasonic generator as in claim **1** wherein said resonator comprises a disc having a free peripheral area, and wherein said clamping means centrally engages said disc.

3. An ultrasonic generator as in claim **1** wherein said resonator comprises an upper resonator, a lower resonator, said upper resonator being contacted by said clamping means, said lower resonator being contacted by said means for engaging said resonator along the line of contact, and additional means for providing a line of contact between said upper and lower resonators, said additional means located between said upper resonator contact and said lower resonator contact lines whereby a larger surface of high vibration amplitude is provided on said lower resonator surface for increasing the rate of atomization of fluids impinging thereupon.

4. An ultrasonic generator as in claim **2** wherein said disc is annular having a plurality of fluid passages leading from the center thereof towards said displacement amplification for delivering fluids thereto.

5. An ultrasonic generator as in claim **1** wherein said resonator comprises a disc having a free central area, and wherein said clamping means peripherally contacts said disc at said one edge.

6. An ultrasonic generator as in claim **5** wherein said disc is annular in shape.

7. An ultrasonic generator as in claim **1** wherein said resonator comprises a tube having an inner wall, an outer wall, and a base, wherein said clamping means comprises a base flange and a relatively thin section connecting said base flange and one edge of said base, and wherein said transducer means contacts said tube along a line of contact near the outer edge of said base.

8. An ultrasonic generator as in claim **1** wherein said resonator comprises a pair of tubes each having a free end, wherein said one edge is a base, wherein said clamping means comprises a base flange for each of said tubes, a relatively thin section connecting each of said flanges to said one edge, and means for fastening said base flanges securely together, wherein said transducer means contacts said one edge along a line on each of said pair of tubes.

9. An ultrasonic generator as in claim **8** together with means adjacent said base for forming a channel for receiving fluids, and wherein said tubes have a plurality of passages therethrough in communication with said channel and extending toward said free end.

10. An ultrasonic generator as in claim **8** wherein said relatively thin section is connected to the central edge of said base flange, and said transducer means contacts the peripheral edge of said base.

11. An ultrasonic generator as in claim **8** wherein said relatively thin section is connected to the peripheral edge of said base flange and said transducer means contacts the central edge of said base.

12. An ultrasonic generator as in claim **1** wherein said resonator comprises a plate having a free end opposite from said one edge, wherein said clamping means comprises a base member, and a relatively thin section connecting said one edge with said base member, and wherein said transducer means contacts said plate near said one edge.

13. An ultrasonic generator as in claim **12** together with means adjacent said base member forming a channel for receiving fluids, and wherein said plate has a plurality of passages therethrough in communication with said channel and extending toward said free end.

14. An ultrasonic generator as in claim 1 wherein said clamping means from said one edge to said transducer means which is less than one quarter wavelength of the driving frequency in the medium of said clamping means.

15. An ultrasonic generator as in claim 1 wherein said transducer means comprises a solid having first and second opposite sides exhibiting displacement due to elastic deformation induced by an electric field, a protective driving member secured to said first side of said transducer for contacting said resonator, an insulator for insulating said second side of said transducer from said clamping means, and electrical connections to said first and second sides from said electrical energy source.

16. An ultrasonic generator as in claim 1 wherein said transducer means comprises a solid having first and second opposite sides exhibiting displacement due to elastic deformation induced by an electric field, a protective driving member secured to said first side for contacting said resonator, additional sides on said transducer means orthogonal to said first and second opposite sides, and means centrally located on said additional sides for connecting one side of said electrical energy source, whereby when said first and second sides are connected in common to the other side of said electrical energy source said transducer provides a driving frequency substantially double that provided when said electrical energy source is connected to said first and second opposite sides.

17. An ultrasonic generator as in claim 1 wherein said electrical energy source has an output terminal and a common terminal and wherein said transducer means comprises at least one pair of transducers exhibiting displacement due to elastic deformation induced by an electric field, first and second opposite sides on said transducers, said first sides being secured together in electrical contact so that said second sides provide displacement 180° out of phase when said transducer means is energized, additional sides on said transducers orthogonal to said first and second opposite sides, means centrally located on said additional sides for connecting said electrical energy source output terminal, whereby when said first and second sides are connected to said common terminal said transducer provides a driving frequency substantially double that provided when said output and common terminals are connected to said first and second sides respectively.

18. An ultrasonic generator as in claim 1 wherein said electrical energy source has an output terminal and a common terminal and wherein said transducer means comprises at least one pair of transducers exhibiting displacement due to elastic deformation induced by an electric field, first and second opposite sides on said transducers, said first sides being secured together in electrical contact so that said second sides provide displacement 180° out of phase when said transducer means is energized, additional sides on said transducers orthogonal to said first and second opposite sides, first means located on said additional sides for connecting said output terminal, second means located on said additional sides for connecting said common terminal, said first and second means for connecting being alternately positioned and equally spaced from one another and said first and second sides whereby when said first and second sides and said second means for connecting are connected to said common terminal and said first means for connecting are connected to said output terminal, said transducer provides a driving frequency substantially a multiple of that provided when said output and common terminals are connected to said first and second sides respectively, said multiple being equivalent to the number of said first connecting means on one of said additional sides of one transducer in each pair plus one.

19. An ultrasonic generator as in claim 1 wherein said transducer means comprises a pair of transducers exhibiting displacement due to elastic deformation induced by an electric field, said transducers having adjacent first sides secured together in electrical contact and opposite facing second sides, a pair of protective driving members secured to said second sides, and electrical connections to said first and second sides from said electrical energy source.

20. An ultrasonic generator as in claim 19 wherein said transducer means have additional sides, together with at least one electrode attached to a selected position on one of said additional sides, said selected position exhibiting a voltage related to said predetermined vibration mode, a source of voltage in phase with the voltage at said selected position and means for connecting said source of in phase voltage to said one electrode for enhancing said predetermined vibration mode.

21. An ultrasonic generator as in claim 19 wherein a varying mass load is applied to the surface of said resonator and wherein said transducer means have additional sides, at least one additional electrode attached to a selected position on one of said additional sides, said selected position exhibiting a voltage related to said predetermined vibration mode, feedback means for receiving said voltage related to predetermined vibration mode, said feedback means connected to said electrical energy source, whereby said transducer is driven to maintain said voltage at said selected position and thereby to maintain said predetermined vibration mode.

22. An ultrasonic generator as in claim 19 wherein said transducers have additional sides and wherein said additional sides exhibit voltages related to vibration modes in the ultrasonic generator, together with at least one electrode overlying a selected area on one of said additional sides, and a ground connection from said one electrode for altering internal transducer electrical fields and suppressing undesirable vibration modes.

23. An ultrasonic generator as in claim 19 wherein said transducers have additional sides and wherein said additional sides exhibit voltages related to vibration modes in the ultrasonic generator, together with at least one electrode overlying a selected area on one of said additional sides, at least one additional electrode overlying a selected area on another of said additional sides, an electrical connection between said selected areas, said selected areas having similar voltage levels but of opposite polarity, whereby internal transducer electrical fields are altered for suppressing undesirable vibration modes.

24. The method of producing ultrasonic energy waves comprising the steps of predetermining the resonant modes of a member, clamping the member dynamically along a line at one end, and driving the member in flexure along a line spaced from the clamping

line, whereby the resonant modes of the member are excited.

25. The method of producing ultrasonic energy as in claim **24** together with the steps of introducing a fluid upon the surface of the member, sensing the loading effect of the fluid, and utilizing the sensed loading effect for controlling the driving frequency of the member to maintain the resonant mode, whereby the fluid is atomized forming a cloud having a predetermined median droplet size.

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