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RESONANT VIBRATORY APPARATUS

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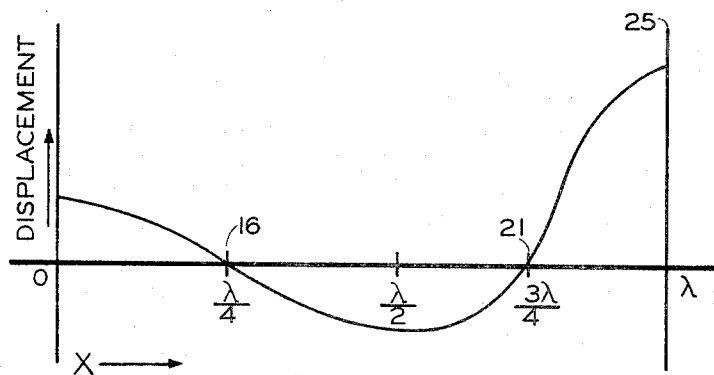
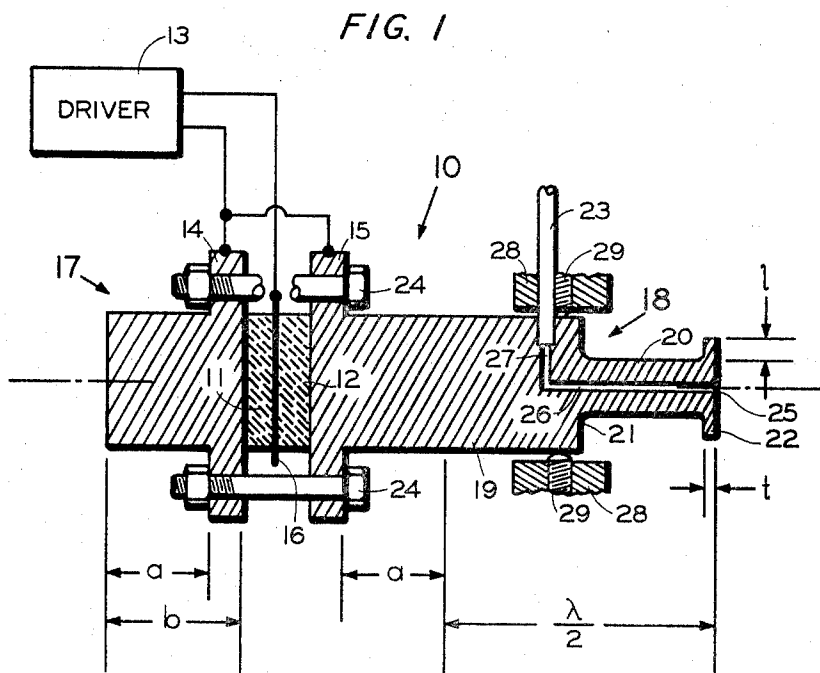


FIG. 2

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RESONANT VIBRATORY APPARATUS

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2 Claims. (Cl. 239-102)

ABSTRACT OF THE DISCLOSURE

A full-wave resonant ultrasonic horn atomizer comprising, from the left: a quarter-wave section 17, two electronically driven, clamped piezoelectric disks 11, 12, and a half-wave section 19, all of full diameter; a quarter-wave section 20 of reduced diameter for mechanical amplification; and a flange 22, supplied with liquid, at the displacement antinode 25, and "tuned" to flex resonantly at the operating frequency.

This invention relates to vibratory apparatus, and particularly to resonant vibratory apparatus having a displacement antinode at an end thereof.

In a typical form of the present invention, resonant vibratory apparatus having a displacement antinode at an end thereof comprises means for supplying liquid to said end, and a resonantly flexible flange at said end. The flange preferably extends outwardly from the end in a plane substantially perpendicular to the direction of vibration of said end.

In a preferred embodiment of the apparatus, the flange comprises a disk of thickness t extending a radial distance l outwardly beyond said end, t and l in inches being chosen substantially in accordance with

$$\frac{t}{l^2} = 6f \sqrt{\frac{\rho}{gE}}$$

where

f is the resonant frequency of said apparatus in c.p.s.,
 ρ the density of the flange material in pounds per cubic inch,
 g is the acceleration of gravity, 386 in./sec.², and
 E is Young's modulus of elasticity of the flange material in p.s.i.

When the apparatus is used for atomizing, the liquid-supplying means furnishes liquid to the face of the flange and the resonant vibration of the flange causes the fluid to spread over the face and become atomized from substantially the entire area thereof.

An important advantage of this invention is exemplified by the substantially increased capacity that it has provided in apparatus such as ultrasonic atomizers as used in miniaturized burners for thermoelectric generators and other military equipment. Conventional ultrasonic atomizers, which may be similar to the atomizer shown in FIG. 1 but without the flange 22, when miniaturized, lose a substantial proportion of their capacities for atomizing fluid. In the present invention, however, the thin resonantly flexible flange increases the effective atomizing area without the usual accompanying loss of displacement that is experienced with flanges and other end pieces that are not tuned to match the resonant frequency of the driving transducer or are not flexible. Miniature atomizers according to the present invention have more than three times the capacity obtainable with comparable atomizers of known conventional designs, with no accompanying disadvantages.

The increase in capacity is not limited to small atomizers. Similar increases of efficiency are realized re-

gardless of the size, where the same basic principles of resonance in the flange are incorporated in the design. Thus at any size the rate of atomization can be increased by a substantial factor over that obtained with conventional units using such acoustic transformers as straight stepped horns. The increase in capacity is attributable partly to the better distribution of the film of liquid across the atomizing surfaces. The distribution of the ultrasonic or sonic stresses across the face of the resonant flange is such that the fluid is drawn out so as to spread across substantially the entire front surface of the flange and become atomized therefrom. Another factor that contributes to the increased capacity is the enlargement of the area over which the effective atomizing forces operate. The effective atomizing forces of a conventional atomizer are condensed about the center (axis) of the horn. In the present invention the effective atomizing forces of the flange extend nearly to the periphery of the flange.

In the drawings:

FIG. 1 is a simplified sectional view of typical resonant vibratory apparatus according to this invention.

FIG. 2 is a graph in rectangular coordinates aligned with FIG. 1 and showing displacement as a function of location along the length of the apparatus of FIG. 1.

In typical ultrasonic atomizers according to this invention, atomization occurs as the result of vibrating a thin film of fuel. The fuel is flowed over the surface of a transducer vibrating at a frequency in the neighborhood of 85 kc. The vibration causes a wave pattern in the fuel over the entire surface area. With sufficient vibration amplitude, the waves throw off droplets from their crests. The droplet size is a function of the atomizer vibration frequency, fuel density, viscosity, and surface tension. The maximum fuel rate depends upon the atomizing area, the frequency and amplitude of vibration, and the uniformity of fuel distribution over the atomization area. The vibrating surface of the atomizer is the end of a small aluminum cylinder that is part of the atomizer; and fuel is supplied to the face of the cylinder through a small axial hole. The atomizer is driven by an electronic driver, which converts 12 v. direct current to high-voltage, 85 kc. alternating current needed to operate the transducer.

FIG. 1 shows a preferred form of such an ultrasonic atomizer. The active elements of the atomizer 10 are two piezoelectric disks 11, 12 of lead-zirconate-titanate material (such as Clevite PZT-4, a product of Piezoelectric Division, Clevite Corporation, Bedford, Ohio), which expand and contract in a thickness mode at the frequency of the driving voltage from a driver 13 placed across the faces of each disk. The disks 11, 12 are clamped between flanges 14, 15 with a foil 16 of copper between them to serve as a center electrode, and with the flanges 14, 15 serving as the outer electrodes. The center electrode 16 is at high voltage, and the outer electrodes 14, 15 are near ground potential, although they are electrically isolated from ground.

The clamping flanges 14, 15 are parts of two aluminum horns 17, 18 which, with the piezoelectric disks 11, 12, form a full-wave resonant vibrator. The electronic driver 13 must provide power at the resonant frequency of the assembly; if this frequency changes slightly with temperature and fuel flow, the driver frequency must also change in order to maintain resonance. This it does. A preferred form of such driver is disclosed in United States patent application Ser. No. 513,171, filed Dec. 13, 1965, of Harvey H. Hunter, for Electronic Oscillators.

The horn 17 to the left of the flange 14 in FIG. 1 is a quarter-wave structure. The atomizing horn 18, to the right of the flange 15, includes a half-wave section 19 at full diameter, plus a quarter-wave section 20 of reduced diameter. The effect of the reduction of cross-section is

an increase in amplitude of longitudinal vibration, inversely proportional to the cross-sectional area. The step shown at 21 provides a mechanical amplification of eight. The flange 22 at the tip of the atomizer 10 is "tuned" to flex at the operating frequency of the atomizer so that the amplification factor is maintained. The flange 22 serves to add atomization area at the tip and thus increase atomizer capacity.

FIG. 1 includes symbols used in the design equations. The relation of vibrational amplitude, or displacement, to axial position on the atomizer 10 is shown in FIG. 2, which is aligned with FIG. 1.

The atomizer 10 can be considered as an acoustic transmission line. The transverse dimensions are small compared to a wavelength and, therefore, the structure simulates a thin bar. The general equation for the acoustic impedance of a thin bar-type transmission line of uniform cross-section is

$$z = -j(\rho c)A \tan \frac{\omega x}{c} \quad (1)$$

where

ρc is the characteristic acoustic impedance of the transmission line material,
 A is the cross-sectional area of the line,
 ω is the angular frequency $2\pi f$,
 f is the frequency,
 c is the velocity of sound in the material of the line,
 x is the distance from the reference point. In the form of Equation 1, $x=0$ is an antinode.

The atomizer 10 is actually a series of short transmission lines joined at points where the acoustic impedances of the mating lines are matched at resonance. In the design stage, the matching is accomplished by applying the appropriate values, which have been predetermined by the design objectives in Equation 1 for each of the mating segments, thus obtaining simultaneous equations that can be solved for the unknown dimensions. For example, in FIG. 1, the components are two 0.5-inch diameter x 0.10-inch thick lead-zirconate-titanate piezoelectric disks 11, 12 sandwiched between aluminum transmission lines 17, 18. The equivalent length of the assembly is one wavelength at 100 kc., with velocity nodes located at the interface 16 between the two ceramic disks 11, 12 and at the step 21 near the feed tube 23. The diameter of the dummy horn 17 and of the larger section 19 of the active horn 18, which is selected to be equal to that of the ceramic disks 11, 12, is 0.5 inch. Other arbitrarily chosen dimensions are:

Smaller diameter of active horn	0.180
Bolt-flange diameter	1.0
Bolt-flange thickness	0.135

The flange 22 at the atomizing tip is matched to the horn 18, so that the dimension identified as $\lambda/2$ is the same as though the flange were not present. Since this dimension includes two quarter-wave segments, its value can be determined by the familiar formula

$$c = \lambda f \quad (2)$$

A quarter-wavelength in aluminum at 100 kc. is approximately 0.503 inch and $\lambda/2$ is 1.005 inch. The remaining horn dimension to be calculated is the length a . This is done by determining the impedance at $x=a$ and at $x=b$, designated as z_1 and z_2 , respectively. The equations are:

$$z_1 = -j(\rho c)_{al} A_1 \tan \frac{\omega a}{c_{al}} \quad (3)$$

$$z_2 = -j(\rho c)_{al} A_2 \tan \frac{\omega [B - (b - a)]}{c_{al}}$$

$$s_1 = -j(\rho c)_{al} A_2 \tan \frac{\omega [B - 0.135]}{c_{al}}$$

$$z_2 = j(\rho c)_c A_c \tan \frac{\omega}{c_c} \left[\left(\frac{\lambda}{4} \right)_c - 0.1 \right]$$

$$z_2 = -j(\rho c)_{al} A_2 \tan \frac{\omega B}{c_{al}}$$

where B would be the length of b if the horn were of uniform diameter. The subscripts c and al refer to the piezoelectric disks and the aluminum, respectively. By introducing the known values into Equation 3 and by using the relationship $(\rho c)_c/(\rho c)_{al}=2.15$, the calculated dimension $a=0.359$ inch.

The atomizer 10, excluding the section identified by the dimensional notation $\lambda/2$, is acoustically symmetrical about the plane 16 that contains the two mating faces of the piezoelectric disks 11, 12. Thus, all of the required dimensions, except those of the flange 22 at the atomizing tip, are now known.

The small flange 22 at the atomizing tip is designed to flex at the resonant frequency of the assembly. The flexural frequency is given approximately by

$$f = 0.537 \frac{t}{l^2} \sqrt{Eg} \text{ (c.p.s.)} \quad (4)$$

for aluminum, where

E is Young's modulus of elasticity, 10,300,000 lb./in.² for aluminum,
 g is gravity, 386 in./sec.²,
 t is the thickness of the flange,
 l is the radial distance the flange extends beyond the small diameter of the horn,

or, rearranging,

$$\frac{t}{l^2} = 1.863 f / \sqrt{Eg} \quad (5)$$

In the previous example, at $f=100$ kc.,

$$\frac{t}{l^2} = 9.65/\text{in.}$$

The dimension l is chosen arbitrarily to increase tip area. With a choice of $l=0.05$ inch, $t=0.024$ inch.

The constant 0.537 includes the density of aluminum, so Equation 4 applies only to aluminum flanges. It can be generalized to

$$\frac{t}{l^2} \approx 2\pi f \sqrt{\frac{0.904\rho}{gE}} \approx 6f \sqrt{\frac{\rho}{gE}}$$

where ρ is the density of the flange material in pounds per cubic inch.

The thin copper electrode 16 between the ceramic disks 11, 12 is assumed to be small enough that it can be neglected with little error in the calculation.

The atomizer 10 of the example above had several resonant frequencies, including one at 100 kc. However, the combination of the atomizer and the final driver performed best at 85 kc., and was used at that frequency in a burner. The flexing flange 22 at the atomizer tip was subsequently tuned for 85 kc.

Although the ultrasonic atomizer 10 appears simple, all parts are highly stressed, and must be made and assembled with care to assure proper operation and satisfactory life. In making the aluminum horns 17, 18, it is extremely important that dimensions be held within ± 0.001 inch, and that the finish be free of tool marks and scratches. Any scratches will act as stress raisers and initiate premature fatigue failure. The active horn 18 should be fully polished, and particular care should be taken with flange fillets.

To insure maximum sensitivity, power transfer, and useful life of the two piezoelectric elements 11, 12 used in the atomizer 10, it is necessary that a compressive force be applied to them. With no coupling agents between the parts of the atomizer, the clamping pressure should be about 13,000 p.s.i. This pressure is obtained by applying a torque of 10.4 in.-lb. to the six bolts 24 used to

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assemble the atomizer. In order to avoid damaging the brittle piezoelectric disks 11, 12, the bolts 24 are first installed finger-tight, and then pairs of diametrically opposed bolts 24 are tightened by small increments, one pair at a time, until the full torque is applied.

Fuel is supplied to the active tip 25 of the atomizer 10 through a small, axial hole 26 extending to meet a radial hole 27 in the large section 19 of the atomizer 10, as close to the step 21 as possible. A 0.032-in.-OD hypodermic tube 23, attached by press-fitting into the radial hole 27, supplies fuel to the atomizer 10. The step 21 is located at a node with zero displacement, providing a good attachment point both for fuel supply and for mounting of the atomizer 10, as in a burner.

Ideally the atomizer should be mounted at a vibration node. However, the node is a plane that shifts as the frequency varies. Frequency shifts occur with changes in atomizer temperature and with changes in thickness of the fuel layer on the atomizer tip. For this reason, any material used for mounting purposes is subjected to some ultrasonic energy. Because of this, the mounting assembly causes a reaction on the assembly that is reflected back into the electrical system. The mount nearly always constitutes a source of loss. Various methods have been tried to minimize the reaction of the mounting system. Perhaps the best mount, from an ultrasonic standpoint, has been two thin polytetrafluoroethylene washers, through which the atomizer was fitted. However, this mount is not suitable for use in a burner. For mounting in a burner, the washers were replaced by an aluminum mounting tube 28 containing six radial screws 29 for clamping to the atomizer 10.

While the form of the invention herein disclosed constitutes a presently preferred embodiment, many others are possible. It is not intended herein to mention all of the possible equivalent forms or ramifications of the invention. It is to be understood that the terms used herein are merely descriptive rather than limiting, and that various changes may be made without departing from the spirit or scope of the invention.

What is claimed is:

1. Resonant vibratory apparatus having a displacement

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antinode at an end thereof, comprising means for supplying a liquid to said end, and a resonantly flexible flange at said end, wherein said flange comprises a disk of thickness t extending a radial distance l outwardly beyond said end, t and l in inches being chosen substantially in accordance with

$$\frac{t}{l^2} \approx 6f \sqrt{\frac{\rho}{gE}}$$

where

f is the resonant frequency of said apparatus in c.p.s.,
 ρ is the density of the flange material in pounds per cubic inch,

g is the acceleration of gravity, 386 in./sec.², and

E is Young's modulus of elasticity of the flange material in p.s.i.

2. In resonant vibratory apparatus having a displacement antinode at an end thereof and means for supplying a liquid to said end, the improvement the comprises providing a resonantly flexible flange at said end, wherein said flange comprises a disk of thickness t extending a radial distance l outwardly beyond said end, t and l in inches being chosen substantially in accordance with

$$\frac{t}{l^2} \approx 6f \sqrt{\frac{\rho}{gE}}$$

where

f is the resonant frequency of said apparatus in c.p.s.,
 ρ is the density of the flange material in pounds per cubic inch,

g is the acceleration of gravity, 386 in./sec.², and

E is Young's modulus of elasticity of the flange material in p.s.i.

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EVERETT W. KIRBY, *Primary Examiner.*

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,400,892

September 10, 1968

Dale Ensminger

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, lines 37 to 39, the formula should appear as shown below:

$$\frac{t}{l^2} \approx 6f \sqrt{\frac{\rho}{gE}}$$

Column 3, lines 73 to 75, the left-hand portion of the formula reading:

$s_1 =$ should read $z_1 =$

Column 6, lines 24 to 27, the formula should appear as shown below:

$$\frac{t}{l^2} \approx 6f \sqrt{\frac{\rho}{gE}}$$

Signed and sealed this 3rd day of February 1970.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents