

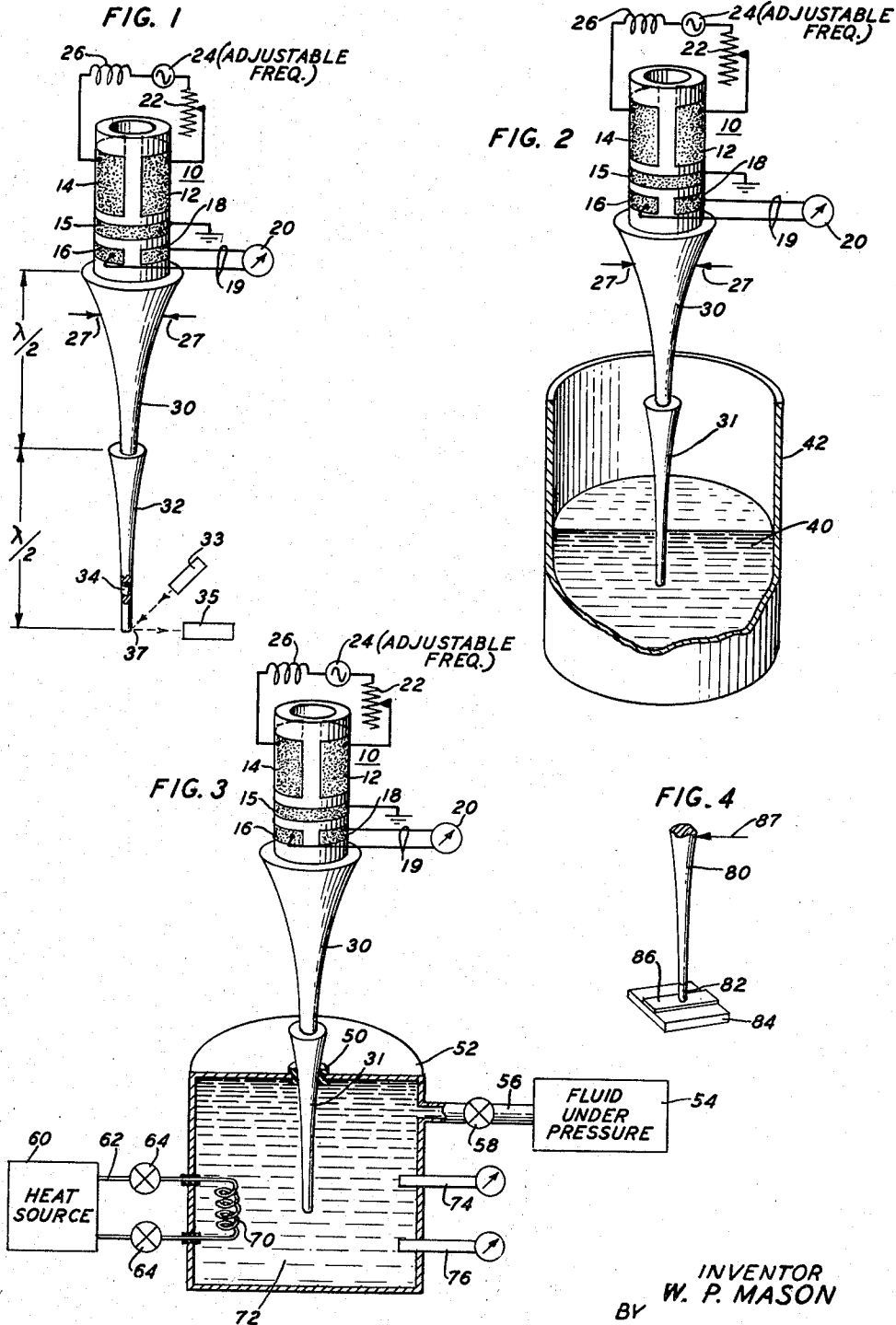
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METHODS AND APPARATUS EMPLOYING TORSIONALLY VIBRATORY ENERGY

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3,131,515 METHODS AND APPARATUS EMPLOYING TORSIONALLY VIBRATORY ENERGY

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This invention relates to methods and apparatus for utilizing mechanical vibratory energy. More particularly, it relates to improved methods and apparatus to afford increased range and scope in the utilization of mechanical vibratory energy.

Apparatus of the prior art adapted for utilizing vibratory mechanical energy of ultrasonic frequencies is represented by that disclosed in applicant's copending application, Serial No. 558,558, filed January 11, 1956, now Patent 2,936,612, granted May 17, 1960, and in applicant's Patents 2,514,080 granted July 4, 1950, and 2,573,168 granted October 30, 1951. (R. F. Wick is joint inventor of the subject matter of Patent 2,573,168.) Such apparatus is utilized for numerous purposes such as obtaining very high particle velocities or measuring, under laboratory conditions, the physical properties of materials, for example, the internal friction and fatigue characteristics or the corrosive action of high velocity fluids on specific solids, or for drilling or welding and for miscellaneous other purposes.

The above-mentioned prior art apparatus makes use of the longitudinal vibration of a mechanical transformer (normally referred to as a horn) which is a tapered solid member of a strong resilient material such as brass and which has a high mechanical quality factor Q . (See, for factor Q , applicant's book entitled "Piezoelectric Crystals and Their Application to Ultrasonics" published by D. Van Nostrand Co., New York City, 1950, Chapter XV, starting at page 390.) Such a tapered horn when driven at its larger end by longitudinally vibratory energy concentrates or amplifies the vibrational energy at the smaller end by a factor which is the square root of the ratio of the area of the larger end to the area of the smaller end. For example, if the area of the larger end is 100 times that of the smaller end, the energy concentration factor is 10.

The theory, advantages and many of the practical applications of the longitudinally vibrating horn type of mechanical transformer are also described in detail in applicant's book entitled "Physical Acoustics and the Properties of Solids" published by D. Van Nostrand Co., 1958, Princeton, New Jersey, see particularly Chapter 6, starting at page 156.

While the prior art type of longitudinally-vibrating tapered horn mechanical transformer, described briefly above, has greatly increased the ranges of particle velocities and stresses readily producible for the operation of various ultrasonic devices and for convenient use in the laboratory testing of specimens of solids and fluids, there are a number of cases in which a further extension of the ranges of particle velocities and stresses would be of great value.

An outstanding example is the problem of adequately testing lubricants which are being subjected to ever increasing strains in the mechanisms of the present era. Undoubtedly many lubricants have considerably different properties at very high strains than they have at the relatively lower strain values to which the majority of prior art testing facilities have been limited.

As a further matter, in the testing of solids for fatigue effects it is well known that the first visible indication of fatigue is the development of surface defects (cracks, et cetera). The provision of instrumentalities for more ef-

fectively concentrating the stress nearer the surface of the test specimen is thus highly desirable and advantageous.

If, simultaneously, the temperature and pressure under which the specimen is being tested can be readily increased and controlled, it is obvious that a much more comprehensive investigation of the properties of the materials being tested can be conducted.

In specialized devices such as ultrasonic welders and drills, the longitudinally vibrating horn has demonstrated much merit. It can be even more effective if rotation can be substituted for its purely longitudinal vibratory motion.

Accordingly, a principal object of the invention is to increase the range and capabilities of conveniently producible particle velocities and stresses for laboratory material testing purposes and for general use in ultrasonic vibratory devices.

Another object is to facilitate the detection of the incidence of fatigue in the testing of solids.

A further object is to facilitate the testing of liquids at higher velocities and stresses.

A still further object is to facilitate the testing of materials at increased temperatures and pressures.

An additional further object is to improve the operation and effectiveness of various vibratory ultrasonic devices, such as ultrasonic drills, ultrasonic welders and the like.

The achievement of the above objects and other objects which will become apparent hereinunder can be realized in accordance with the present invention principally by substituting a torsionally driven mechanical transformer or horn for the longitudinally driven mechanical transformer or horn of the prior art arrangements. This is so since applicant has discovered that for a torsionally vibrating mechanical transformer of the tapered horn type the maximum particle velocities and stresses sustained toward the smaller end of the vibrating mechanical transformer member (horn) vary inversely with the cross-sectional area ratio between the large and small ends instead of inversely with the square root of the area ratio, as for the prior art longitudinally driven horn. It thus becomes readily feasible to subject the test specimens to much greater particle velocities and stresses than with the prior art longitudinally vibrating horn. Torsional vibration furthermore offers distinct advantages in the fatigue testing of solids since it concentrates more energy near the surface of the specimen where the signs of fatigue are first apparent. Also, in the testing of liquids and for incidental uses such as drills, welders, and the like, the greater power to which the specimen or work piece can be subjected by use of torsional vibration is obviously distinctly advantageous.

Other objects, features and advantages of the invention will become apparent during the course of the following detailed description of illustrative embodiments shown in partly diagrammatic form in the accompanying drawings.

In the drawings:

FIG. 1 illustrates an arrangement of the invention for testing solid materials;

FIG. 2 illustrates an arrangement of the invention for testing liquids;

FIG. 3 illustrates an arrangement of the invention for testing specimens under elevated pressure and temperature; and

FIG. 4 illustrates the provision of a drill or welding point on the lower end of a horn of the invention.

In more detail in FIG. 1, transducer 10 is of the ferro-electric type and, by way of example, may employ a cylinder consisting principally of barium titanate. It is polarized and driven by main electrodes 12 and 14 to vibrate torsionally when alternating current from source 24 is applied to the electrodes. Transducer 10 can be of

the general type described and claimed in applicant's Patent 2,742,614, granted April 17, 1956, improved as suggested and claimed in applicant's Patent 2,880,334, granted March 31, 1959. Among numerous other forms of ferroelectric torsional wave transducers which could be employed for the purposes of the present invention are those shown in FIGS. 5 and 6 of applicant's Patent 2,828,470, granted March 25, 1958. Alternatively, numerous forms of magnetostrictive and piezoelectric electromechanical torsionally vibratory transducers could, obviously, be employed in place of the transducer 10 described above.

On the lower end of transducer 10, two small electrodes 16 and 18 are provided and connected through leads 19 to indicator 20, thus providing an indication of the amplitude of the vibratory motion being developed by transducer 10. A ring electrode 15 surrounding transducer 10 between the small electrodes 16, 18 and the large electrodes 12, 14 is grounded and minimizes the likelihood of electrical crosstalk or leakage between the two pairs of electrodes.

An inductance 26 is placed in series with the transducer 10 and source 24 to resonate the distributed capacity between the electrodes 12, 14 at substantially the frequency at which the transducer is to be driven. A rheostat 22 included in series with source 24 provides a convenient control of the power supplied to transducer 10. Usually, for the above-mentioned testing of solid and liquid materials and miscellaneous other uses, a frequency of about 18 kilocycles is chosen so that sonic waves radiated from the vibrating portions of the system will be above the audible frequency range and therefore will not cause annoyance to people in the vicinity.

The lower the frequency, however, the larger the transducer and horn dimensions may be so that in some instances the inconvenience or annoyance which may be caused by audible vibrations may be less than the convenience resulting from being able to employ apparatus of larger dimensions. The frequency of source 24 should be adjustable so that it can be accurately tuned to the frequency of resonance whatever kind of test specimen 34 is inserted in horn 32. Also, as is well known to those skilled in the art, viscosity and elasticity tests of fluids are based in part upon observations of the effect of the fluid on the frequency of resonance of the system.

The tapered horn, or mechanical transformer 30, has its larger end secured, usually by solder or cement, to the lower end of transducer 10, the horn 30 and transducer 10 and the second tapered horn or mechanical transformer 32 being located along a common longitudinal axis, as shown.

Horns 30 and 32 are each conveniently made one or more integral half wavelengths long at the driving frequency. Since torsional vibratory waves in general travel at substantially one-half the speed of longitudinal vibratory waves, the horns required for arrangements of the invention need be only approximately half the length which would be required if corresponding longitudinally vibrating horns operated at the same frequency were to be used.

Though substantially any mode of continuous taper will provide mechanical transforming action, an exponential taper lends itself more readily to theoretical analysis and is therefore often considered preferable. In the embodiments of the accompanying drawing, the usual arrangement of two horns in tandem, each one-half wavelength long, is employed. This facilitates interchange of the second horn to substitute one with a different test specimen in it or a horn with no test specimen for a comparison test. A threaded joint of conventional type preferably should be provided between the upper and lower horns to further facilitate interchanging the second horn.

Horn 30 can, for example, have a ratio of maximum to minimum diameters of 10 to 1 (area ratio 100 to 1).

Horn 32 can conveniently have a maximum diameter of twice the minimum diameter of horn 30. Horn 32 can have a minimum diameter of one-quarter its maximum diameter (area ratio 16 to 1). The overall effective "step-up" provided by the two horns connected mechanically in tandem as shown, and driven torsionally, would then be 1600 to 1. This contrasts with the overall effective step-up of only 40 to 1 (that is, the square root of 1600) which would be obtained if horns driven longitudinally as taught by the prior art were employed. In many instances, particularly where a plurality of different specimens are not to be measured, a single horn such as 30 will often provide an entirely adequate step-up when torsionally vibratory energy is employed.

To avoid higher mode torsional vibrations the requirements of relation (2.138) given at page 49 of applicant's above-mentioned book "Physical Acoustics and Properties of Solids" should be observed. The above-mentioned relation (2.138) is

$$2a = \frac{3}{4} \frac{5.136V}{\pi f}$$

where a is the maximum radius of the rod, f is the frequency of the torsional driving energy and V is the velocity of the torsional waves in the rod. The avoidance of higher order torsional vibrations is of particular importance in connection with the present invention since such vibrations result in dispersion and dissipation of much of the energy and could well overbalance the advantages of increased particle velocities and stresses at the smaller end of the rod or member which are required in order that the objects of the invention may be realized.

By setting test specimen 34 into the smaller end of horn 32 (that is, in effect, replacing a similar bit of the horn by the test specimen) at a distance of approximately 20 percent of the total length of the horn from its smaller extremity, the specimen 34 will be subjected to substantially the maximum stress developed by the two horns 30, 32 operating in tandem. For comparison purposes, as taught for example in my above-mentioned copending application, Serial No. 558,558, now Patent 2,936,612, a horn precisely like 32, except that no test specimen has been introduced into its lower portion, should be tested under identical conditions as for tests of the horns which include test specimens.

Because of the torsional vibratory drive employed, a major portion of the applied energy is concentrated in the outer portion of specimen 34 and will therefore tend to develop the telltale cracks in its surface, indicating the inception of fatigue in the material of the specimen, at a much lower level of driving energy to the top surface of horn 30 than would be required were the horns driven longitudinally as taught in the prior art. Furthermore, by measuring the ratio of the input voltage to the output voltage at resonance, an indication of the internal friction is obtained. The internal friction has been shown to be an indication of the type of mechanism causing fatigue (see section 94, pages 255 to 265 of applicant's above-mentioned book "Physical Acoustics and the Properties of Solids." Since the internal friction of a torsionally vibrating sample is affected primarily by the material on the outside of the sample, it will provide a better correlation with fatigue properties.

The energy required to produce the indicia of fatigue can be even further reduced by drilling a vertical hole through the center of the specimen 34 before mounting it in horn 32, as shown.

Conversely, many specimens of stronger materials, such for example as certain alloy steels, can be carried to the fatigue point quite easily by use of the increased concentration of power made available by the torsionally driven horns of the invention, whereas it would be much more difficult, if indeed not impossible, to adequately test specimens of such stronger materials using longitudinally driven horns as taught by the prior art.

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A small bright spot can be made by a sharp pointed instrument near the lower end of horn 32 and a beam of light from spotlight 33 directed to impinge upon it. Viewing it through microscope 35 when the horn is vibrating torsionally the spot will appear as a horizontal line the length of which will represent the magnitude of the vibratory motion of the lower end of horn 32. A scale can be engraved on the end of microscope 35 to facilitate observation of changes in the length of the line. Thus the stress amplitudes at which creep and fatigue begin to develop can be observed in substantially the same manner as taught in my above-mentioned copending application, Serial No. 558,558, now Patent 2,936,612, for a longitudinally vibrating system.

As planes of no motion occur at a distance of substantially twenty-five percent of the length of each horn from its larger end, fixed supports 27 can support the assembly of FIG. 1, at such a plane, as shown. Alternatively, the assembly of FIG. 1 could be supported by an appropriate fixed support at the appropriate distance below the upper end of horn 32 or by appropriate fixed supports at each such plane of each horn.

In FIGS. 2 and 3, other applications of a transducer and torsionally driven double horn arrangement substantially like that of FIG. 1 are shown and like portions of the three figures are given the same designation numbers, respectively. Such like portions are, of course, to be understood to be as described above in connection with FIG. 1.

In FIG. 2, horn portion 31 can be identical with horn portion 32 of FIG. 1 except that no test specimen 34 of FIG. 1 is included in horn portion 31 of FIG. 2 since in the arrangement of FIG. 2 it is desired to test the properties of the liquid 40 contained in vessel 42 to determine, for example, its viscosity and elasticity. The horn assembly of FIG. 2 can conveniently be supported on fixed supports 27 so that the lower end of lower horn 31 protrudes into liquid 40 as shown. Because of the substantially increased velocities and stresses which can be generated by the torsionally driven horns and the greater "drag" of a torsionally vibrating driven member as compared with a longitudinally vibrating member in the liquid, the viscosity and elasticity of liquid 40 can be tested for conditions much more nearly, if indeed not precisely, simulating the more severe operating conditions to which, for example, lubricants are likely to be subjected in many present day mechanisms.

In FIG. 3 the enclosing vessel 52 is further arranged so that it can enclose the lower portion of horn 31 from its plane of no motion, downwardly. For this purpose a tight packing gasket 50 is included at the stationary plane to provide a high pressure seal between vessel 52 and horn 31.

Vessel 52 is filled with a fluid 72 to be tested. The pressure of the fluid 72 can be increased by opening valve 58 in pipe 56 which connects to a source 54 of the fluid to be tested under appropriately higher pressure. The pressure in source 54 should, of course, be sufficient to permit testing the fluid 72 at the maximum pressure for which its properties are to be determined. In like manner the temperature of the fluid 72 can be raised by opening valves 64 in pipe 62 connecting to heat source 60. Suitable conventional pressure and temperature gauges 74 and 76, respectively, are, obviously, convenient adjuncts for the conduct of tests. Tests at appropriately elevated temperatures, pressures and energy levels to accurately simulate much more severe operating conditions than can be simulated by prior art instrumentalities convenient for general laboratory use accordingly can be readily conducted by the arrangement illustrated in FIG. 3.

By measuring the change in the resonant frequency resulting from immersion of the end of horn 31 in the fluid and the resulting change in the quality factor Q of the system, the viscosity and shear elasticity of the fluid can be determined. The method of calibration is similar to that disclosed in applicant's Patent 2,518,348 granted August 8, 1950.

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In FIG. 4 the lower end 80 of a horn of the invention such as horn 31 of FIGS. 2 and 3 is shown with its tip end replaced by a hardened point 82. When driven torsionally as for FIGS. 2 and 3, such an assembly makes a most effective drill for precision drilling such as dental work or in the manufacture of delicate mechanisms. By using abrasives with the drill, circular holes can be quickly cut in brittle materials. The same horn assembly can perform welding operations as, for example, the welding of a thin metal strip 86 to a metal block 84. Moderate vertical pressure on the horn assembly combined with the torsional vibrations will effect a spot-by-spot welding of strip 86 to block 84. Lateral pressure 87 on horn 80 is applied at the plane of no motion to move the horn assembly along strip 86. In view of the small area of the lower end of horn 80, 82 a small pressure on the assembly will result in a very considerable pressure of point 82 on strip 86. For welding operations of the type just described a pressure at point 82 of approximately 5000 pounds per square inch should be used.

Numerous and varied other arrangements and modifications of the arrangements described hereinabove can readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. Apparatus for generating vibratory energy of very high particle velocities comprising a longitudinally tapered resilient rod having a length between the ends of an integral number of half wavelengths of a torsionally vibratory energy wave of a predetermined frequency, the tapered rod having a maximum diameter not greater than that specified by the relation

$$2a = \frac{3}{4} \frac{5.136V}{\pi f}$$

where a is the maximum radius of the rod, f is the frequency of the torsional driving energy and V is the velocity of the torsional waves in the rod, and means for driving the larger end of the rod by torsionally vibratory wave energy of the predetermined frequency.

2. A method of obtaining very high particle velocities which comprises establishing standing vibratory torsional waves in a solid longitudinally tapered member of circular cross section, the member having a maximum diameter not greater than that specified by the relation

$$2a = \frac{3}{4} \frac{5.136V}{\pi f}$$

where a is the maximum radius of the member, f is the frequency of the torsional driving energy and V is the velocity of the torsional waves in the member, the member having an approximate antinode at its larger end and a nodal plane near its smaller end, whereby the increased concentration of vibratory torsional wave energy in the nodal plane of the member having a relatively small cross section is obtained.

3. A drilling device comprising a longitudinally tapered resilient rod having a length of an integral number of half wavelengths of a torsionally vibratory energy wave of a predetermined frequency, the tapered rod having a maximum diameter not greater than that specified by the relation

$$2a = \frac{3}{4} \frac{5.136V}{\pi f}$$

where a is the maximum radius of the rod, f is the frequency of the torsional driving energy and V is the velocity of the torsional waves in the rod, a drilling bit fastened to the smaller end of the rod, and means for driving the larger end of the rod by torsionally vibratory energy of the predetermined frequency.

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