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Description

The present invention concerns an apparatus for exciting motion in a liquid contained in a vessel by means of ultrasonics for cleaning and/or penetration of an object at least partially submerged in the liquid, and including at least one ultrasound transducer in physical contact with the vessel.

Background of the invention

Cleaning apparatus using ultrasonics in a conventional manner has an important disadvantage. In spite of the fact that ultrasound should be sound at frequencies above the audible range there are always one or more subharmonics, for example at half the fundamental frequency, which are audible and strong. These strong tones are firstly an irritant for personnel, and secondly (in many cases) a potential cause of hearing damage. It is necessary to either enclose the ultrasonic apparatus or place it in a room where personnel need not be exposed to the strong tones.

The theory of how these subharmonics are generated is quite inadequate. It is generally accepted that the subharmonics are generated in connection with cavitation in the bath. Subharmonics are generated when the sound pressure in the liquid exceeds a threshold value, between two and four atmospheres (the threshold value for cavitation is about one atmosphere).

In known ultrasonic apparatus a transducer is used whose contact surface against the bottom of the vessel is as large or larger than the active element, which is often a piezoelectric ceramic. This means that the whole contact surface moves up and down in time with ultrasound to generate sound in the bath. Such a surface, which is a number of sound wavelengths in size, radiates efficiently into the bath, that is, the radiation coefficient is near unity. This also means that all the energy that enters the bath penetrates exactly that limited area. In a bath with a volume of one liter one usually wants about 50 watts of input acoustic power. If the contact surface is about 5 x 5 cm one gets 2 watts/cm² input power, which is complemented by power reflected from the limiting surfaces of the bath, and which further increases the intensity by a factor of two or more. In this way the subharmonic regime is reached, and the apparatus is clearly audible. The situation is even worse when working with larger baths and higher power from a small number of transducers.

Naturally the bath's or vessel's other limiting surfaces also radiate sound to the bath, but that radiation is rather ineffective. This is because the vessel is made of thin metal, usually stainless steel, with a thickness of 0.4 mm, and the ultra-

sonic vibrations are transmitted in the form of bending waves (for stainless steel of thickness 0.4 mm and at 40 kHz the wavelength of the bending waves is 10 mm). These bending waves radiate poorly. The radiation efficiency is about 0.01. Therefore it is very difficult to obtain a high radiation intensity from such a surface, whose contribution to the total radiation is insignificant. Rather, the radiation is concentrated to the contact surface of the transducer, where the intensity is high. The result, as is well known, is that the transducer generates strong audible subharmonics. Their production is connected with the way the ultrasonic transducer (normally containing one or more piezoelectric ceramics) is made, and its attachment to the vessel. The subharmonics are therefore not produced by the electrical power supply per se, but rather have an acoustic cause.

Today there are two designs on the market. The most common is cylindrically symmetric and is attached to the vessel's underside. A conical front piece is glued to the vessel with the base of the cone (typical diameter 45 mm) as the contact surface. The other end of the cone (typical 35 mm) is attached to one or a pair of piezoelectric ceramics of diameter 35 mm and thickness 6 mm stacked on each other. On the back side of the piezoelectric ceramics there is a short cylinder (back piece), diameter 35 mm and thickness 10 mm. This transducer is held together by a bolt which goes through the center of the transducer. Electrodes provide the piezoceramics with the voltage. The total thickness is 40 mm, and the transducer has a working frequency of 40 kHz, corresponding to a vibration resonance in the transducer. In this design the front piece is designated positively coned. This transducer can transmit maximally about 50 watts of ultrasound to the bath, according to the manufacturer. The probable reason for this limit is that the ultrasound must be transmitted through a limited area (diameter 45 mm) to the bath, whence the intensity is high. When this intensity becomes too high, a cavitation pillow in the liquid outside the transducer is formed which effectively limits power transmission (see for example Theodor F Hueter & Richard H Bolt, *Sonics*, Wiley, New York, 1955, page 232). If more ultrasonic power is needed in the bath more transducers must be used.

The other type of transducer is disc-shaped and contains a piezoelectric ceramic in the form of a plate which is attached to the vessel with its plane side as contact surface. Such a transducer has a diameter of about 40 mm. Such transducers are very simple, but they are relatively inefficient, and they are therefore used mainly in applications where the desired ultrasonic power is low.

The acoustic bending wave wavelength in

these vessels is about 10 mm for frequencies around 40 kHz. The contact surfaces of the above transducers are therefore several bending wave wavelengths in size, and about as large as a wavelength in water at these frequencies. This means that the ultrasound that is generated in the transducer is radiated out into the fluid through exactly that surface so that the intensity of the ultrasound is approximately the ultrasound power divided by the contact surface. This also means that a "shadow angle" is formed, so that only that part of the bath volume that is within a calculable angle from the normal (usually between 45 and 60 degrees) is irradiated directly with ultrasound. To get a strong ultrasonic field in the fluid the intensity in the fluid outside the transducer must be high.

It is exactly this high ultrasonic intensity that causes subharmonics and audible sound. High ultrasonic intensities should be avoided, partly because they impose a limit to the power that can be transmitted to the bath, and partly because they cause subharmonics and audible tones. The latter has been studied in detail by Werner Lauterborn et al (see for example Physics Today, January 1986, page S-4, and references therein).

The purpose of the invention and its main characteristics

The purpose of the present invention is to achieve a simple and inexpensive instrument for silent ultrasonic treatment, and which can transmit high ultrasonic powers to fluids. These goals have been realized by making the diameter or diagonal of the ultrasonic transducer's contact surface against the vessel smaller than or equal in size to a bending wave wavelength in the vessel material and to a sound wave wavelength in the liquid. The transducer can be used at several different frequencies, either one at a time or in combination. The ultrasonic power in a fluid in a vessel can be kept high while at the same time the ultrasonic intensity at the limiting surfaces of the vessel remains relatively low. This means that subharmonics are absent and that ultrasonic irradiation of an object in the fluid comes from many different directions simultaneously.

Description of the drawings

In the following the invention will be described in detail with reference to an embodiment of the invention shown on the attached drawing.

Fig. 1 shows a section through an instrument for ultrasonic generation according to the invention.

Fig. 2 shows a perspective view of a transducer according to the invention.

Fig. 3 is a diagram of measurement results

from comparison tests.

Description of an embodiment

The invention consists of the ultrasonic transducer's contact surface's being limited to a very small area. By small is meant an area whose diameter is smaller than or of the same order of magnitude as the bending wave wavelength is the vessel's walls, and whose diameter is simultaneously also smaller than a sound wavelength in the liquid that is in the bath. For water and a frequency of 40 kHz the sound wavelength is about 35 mm. With these limits one avoids having a radiating surface where the radiation efficiency can be near unity. This means in turn that the sound pressure cannot exceed the threshold value for subharmonic generation, and the bath is silent.

The ultrasonic energy must still be transmitted to the liquid in the bath. This takes place through the above mentioned bending waves in the vessel, which is assumed to be made of a thin material, for example 0.4 mm stainless steel. The whole vessel vibrates, which means that there is a radiating surface of about 500 cm² for one liter of liquid. With a radiation intensity of only 0.1 watt/cm² there is still 50 watts of ultrasound in the bath. This radiation intensity is less than 5 % of the intensity that is reached in today's ultrasonic apparatus, not counting reflections, in spite of the fact that the ultrasonic energy in the bath is the same, 50 watts/liter. The invention further allows generation of the desired ultrasonic energy in a bath without concentrating the intensity to the contact surface of the transducer.

Ultrasonic powers of over 100 watts in one liter baths have been achieved without detectable subharmonics. Further, four such transducers have been applied to a larger bath (12 liters) and generated over 300 watts of ultrasonic power in that bath without audible subharmonics. At the same time it has been possible to measure the same cleaning efficiency in the one liter bath according to the invention as in conventional ultrasonic baths of the same size. Using hydrophones it has been possible to show the presence of cavitation in both cases.

The instrument according to the invention consists of a housing 7 in which there is a vessel 8, for example made of stainless steel.

Attached to the bottom 9 of the vessel is a transducer 1 which will be described below in detail. A generator is designated 10.

The transducer according to the invention is shown one embodiment in figure 2. Such a transducer 1 can for example consist of a front piece 3, one end of which is shaped as a truncated cone 2 with a concave surface 2a. The top surface of the

cone or its contact surface 2b against the vessel has an appropriate diameter of 7 mm. The front piece 3 made of aluminium, which for a metal has a relatively low acoustic impedance, and has a total length of 25 mm. The conical part 2 of the front piece has a length of 11 mm. The conical shape should show a continual transition between the front piece's base diameter (25 mm) and the contact surface 2b (7 mm). The back piece 6 of the transducer is made of steel, which for a metal has a relatively high acoustic impedance. It is 24.9 mm long. Between the front piece and the back piece there is a piezoelectric ceramic 5 (thickness about 2 mm) and an electrode 4. For safety reasons there is a thin ceramic disc placed between the electrode and the front piece, in order to insulate it electrically. Electrical current with the desired frequency is coupled to the transducer via the electrode 4 and the back piece 6. It is also possible to have a transducer with two piezoelectric ceramics stacked on each other and two additional electrodes.

The whole transducer is glued together with heat cured epoxy glue, in contrast with most conventional transducers which are held together by central bolts. Experience shows that the glue works well and simplifies production. The contact surface 2b of the transducer is glued to the steel vessel which can have a wall thickness of 0.4 mm. In this embodiment the three lowest vibration resonances of the transducer are about 45 kHz, about 100 kHz, and about 170 kHz. One and the same transducer can be used for any of these frequencies, and it can deliver at least 100 watts of acoustic power to a water bath in the vessel 8.

Naturally the transducer can have other dimensions, depending on which frequencies are desired to be generated and what powers are required. The transducer does not need to be glued together either, but rather it can be bolted together. Further it is possible to replace the different materials (aluminum and steel) with other materials if such is desirable in a certain application. It is not necessary to use a piezoelectric material, and magnetostrictive materials or other materials can be used. The important thing is that the transducer's contact surface 2b is smaller than or of the same order of magnitude as the bending wave wavelength in the vessel and the sound wavelength in the fluid that is to be excited by the ultrasound.

A 0.6 mm thick ceramic disc is placed between the front piece and the electrode to insulate the front and vessel electrically from the electrical system. Naturally materials other than ceramics can be used, and other thicknesses. It can also be advantageous to use the ceramic disc (or its equivalent) in a mechanical support system for the transducer as a whole. As is known, mechanical contacts with the ultrasonic transducer should be

avoided as they can disturb the resonance picture and take away ultrasound in an undesirable manner. A way of achieving a mechanical contact which does not have these deficiencies is to attach the mechanical support at or near a velocity node on the transducer. The ceramic disc is near such a node and can therefore be used as a support point without disturbing the transducer's function. Today's ultrasonic transducers for cleaning purposes can transmit only 50 watts of ultrasound to the bath from each transducer. This has to do with the design of the transducer. The ultrasonic transducer according to the invention is not affected by the same limit, but rather it has been shown to be able to transmit more than 100 watts of ultrasound to a corresponding bath. Further it is possible to measure how fast contaminants are removed from an object in an ultrasonic bath. This cleaning is quicker in an ultrasonic instrument according to the invention. One of the reasons for these good results can be development of cavitation (desirable in connection with cleaning) without subharmonics if the sound pressure is kept over the threshold for cavitation (one atmosphere sound pressure or one watt/cm² intensity) and under the threshold for subharmonics (at least two atmospheres sound pressure or at least 4 watt/cm² intensity). The invention makes exactly that possible.

In figure 3 measurement results for the transducer according to the invention are shown. The rate at which a fingerprint disappears from a titanium surface when it is treated with ultrasound (about 40 watts in 0.9 liters of water at 25 °C, or equivalent powers in larger baths) is shown. The vertical axis shows the percentage of the fingerprint that has disappeared (measured electrochemically using the Galvani potential, see for example D H McQueen, "Electrochemical evaluation of ultrasonic cleaning: the Galvani potential", Ultrasonics 24, 49 (1986)), and along the horizontal axis the time is shown. Curve "a" has been obtained with a conventional apparatus which works at a frequency of 47 kHz and which generates strong audible tones. The other curves have been obtained with silent ultrasonic instruments according to the invention. The curve marked "b" is for 45 kHz; the curve marked "c" is for 100 kHz; the curve marked "d" is for 170 kHz. The highest curve, marked "e", is for a combination of 45 kHz ultrasound (half the power) and 170 kHz ultrasound (half the power), with a total ultrasonic power equal to the ultrasonic power that was used for the three other measurements according to the invention. Similar curves have been obtained for industrial grinding paste instead of fingerprints. The process is quicker when higher temperatures and better solvents are used.

The reason that conventional apparatus show poorer cleaning efficiency is that the ultrasound is

radiated into the bath from a limited surface defined by the transducer's contact surface, and a shadow angle is formed. The object to be cleaned is irradiated mainly from a single direction. The other curves, for the instrument according to the invention, show the increasing cleaning efficiency. As the frequency is increased faster cleaning is achieved, in accordance with the theory that was presented by McQueen (Ultrasonics 24, 273 (1986)). The highest curve, which is a combination of low and high ultrasonic frequencies, should give a result corresponding to an average of those two frequencies. That is not the case, and instead an unexpected higher result is obtained. The same good result is obtained with industrial grinding paste on titanium surface. The transducer according to the invention is especially well suited to make use of this positive result, as it can be used at two or more frequencies at the same time. Naturally it is appropriate that the frequencies be different, for example one frequency should be at least fifty percent higher than the other. This does not necessarily exclude choosing 20 kHz and 30 kHz, but it is clear from figure 3 that it is better to use one frequency between about 30 kHz and 50 kHz and the other frequency over about 100 kHz. It should be remembered that higher frequencies can be more efficient at cleaning, and that higher frequencies can penetrate into tight spaces, in precision mechanical devices, for example, better than lower frequencies can.

According to a modified embodiment the transducer according to the invention is equipped with a front piece which has more than one narrowed part and also several contact surfaces. The transducer that has been described above has only one narrowed part toward the vessel. The limited, small contact surface can be a mechanically weak point, because it is relatively easy to break the transducer away from the vessel at that point. If one and the same transducer is provided with two or three or more such contact points the whole transducer will be more stable mechanically. Of course each point must have a contact surface which is less than a water wavelength and a bending wave wavelength in size.

Of course the invention is not limited to the examples above, but can be varied within the frame of the principles that have been mentioned. Further, the application of the invention is not restricted to cleaning solid objects in a liquid bath, for instance precision mechanical devices, electrical and electronic components (circuit boards, ceramic substrates, silicon wafers, integrated circuits, etc), optical components (lenses, filters, fiber optics, etc), even if ultrasound has been shown to be excellent for cleaning surface mounted circuits. The invention can advantageously be used

in process industries, for example electrochemical processes such as electroplating, biochemical processes such as cell growing, catalytic processes such as sewerage cleaning, separation processes such as ultrafiltration and chromatography, leaching processes, etc. Further the frequency regime which is intended here is not restricted either toward lower or toward higher frequencies. The transducer's power can be increased to several hundred watts or reduced to a few watts, for example by changing its diameter.

Claims

1. Apparatus for exciting a liquid in a vessel (8) by ultrasound for cleaning and/or penetration of an object at least partially immersed in the liquid, and including at least one ultrasonic transducer (1-6) arranged in contact with the vessel (8),
characterized by
the diameter or diagonal of the ultrasonic transducer's contact surface (20) against the vessel (8) being smaller than or equal to both the bending wave wavelength in the vessel material and the sound wavelength in the liquid.
2. Apparatus according to claim 1,
characterized by
the ultrasonic transducer's being arranged to produce a combination of high and low frequencies, either superimposed from the same transducer or different frequencies from different transducers.
3. Apparatus according to claim 1 or 2,
characterized by
the end part (2) of the transducer's (1) front piece (3) connected to the vessel (8) being shaped like a truncated cone, pyramid, obelisc or the like with a concave surface (2a), the top surface (2b) of the cone being the contact surface against the vessel (8) which is connected to the contact surface by a joint, appropriately a glue joint.
4. Apparatus according to claim 3,
characterized by
the front piece (3) being shaped to include several truncated cones (2) where each top surface is connected to the vessel (8) and where each top surface/contact surface has a diameter or diagonal smaller than or equal to both the bending wave wavelength in the vessel material and the sound wavelength in the liquid.

Patentansprüche

1. Vorrichtung zur Bewegungserregung in einer in einem Gefäß (8) enthaltenen Flüssigkeit mittels Ultraschall zum Reinigen und/oder Durchdringen eines zumindest teilweise in die Flüssigkeit eingetauchten Objekts, und die mindestens einen mit dem Gefäß in physischem Kontakt befindlichen Ultraschallwandler (1-6) aufweist, gekennzeichnet dadurch, daß
 der Durchmesser oder die Diagonale der Kontaktfläche (20) des Ultraschallwandlers zum Gefäß kleiner oder genauso groß sowohl wie die Wellenlänge der Beugungswelle im Gefäßwerkstoff und die Schallwellenlänge in der Flüssigkeit ist. 5
2. Vorrichtung nach Anspruch 1, dadurch gekennzeichnet, daß
 die Ultraschallwandler so angeordnet sind, daß eine Kombination hoher und niedriger Frequenzen erzeugt wird, entweder vom gleichen Wandler übereinandergelagert oder verschiedene Frequenzen von verschiedenen Wandlern. 10
3. Vorrichtung nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß
 das mit dem Gefäß (8) verbundene Endstück (2) des oberen Teils (3) des Wandlers (1) die Form eines Kegelstumpfes, einer Pyramide, eines Obelisks oder ähnlichem mit einer konkaven Oberfläche (2a) aufweist, wobei die Deckfläche (2b) des Kegels die Kontaktfläche zum Gefäß (8) ist, das durch eine Verbindung, angemessenerweise eine Klebverbindung, mit der Kontaktfläche zusammengefügt ist. 15
4. Vorrichtung nach Anspruch 3, dadurch gekennzeichnet, daß
 das obere Teil (3) mehrere Kegelstümpfe (2) umfassen kann, wobei jede Deckfläche mit dem Gefäß (8) verbunden und jede Deckfläche/Kontaktfläche einen Durchmesser oder eine Diagonale hat, der oder die kleiner als bzw. genauso groß wie die Wellenlänge der Beugungswelle im Gefäßwerkstoff und die Schallwellenlänge in der Flüssigkeit ist. 20

Revendications

1. Dispositif pour exciter un liquide dans un récipient (8) par ultrason afin de nettoyer et/ou de pénétrer un objet immergé au moins partiellement dans le liquide, et comportant au moins un transducteur ultrasonique (1-6) disposé en contact avec le récipient (8), caractérisé en ce que le diamètre ou la 25

diagonale de la surface (20) du transducteur ultrasonique en contact avec le récipient (8) est plus petit ou égal à la longueur d'onde de flexion dans la matière du récipient ainsi que la longueur d'onde du son dans le liquide.

2. Dispositif selon la revendication 1, caractérisé en ce que le transducteur ultrasonique est disposé de façon à produire une combinaison de hautes et basses fréquences, soit superposées en provenance du même transducteur, soit de fréquences différentes en provenance de transducteurs différents.
3. Dispositif selon la revendication 1 ou 2, caractérisé en ce la partie extrême (2) de la pièce antérieure 3 du transducteur (1) reliée au récipient (8) a la forme d'un cône tronqué, d'une pyramide, d'un obélisque ou analogue avec une surface concave (2a), la surface supérieure (2b) du cône étant la surface de contact contre le récipient (8) qui est reliée à la surface de contact par un joint, de manière appropriée par un joint de colle.
4. Dispositif selon la revendication 3, caractérisé en ce que la pièce antérieure (3) est façonnée de manière à comprendre plusieurs cônes tronqués (2) où chaque surface supérieure est reliée au récipient (8) et où chaque surface supérieure/surface de contact a un diamètre ou une diagonale inférieur ou égal à la longueur d'onde de flexion dans la matière du récipient et à la longueur d'onde du son dans le liquide. 30

FIG. 1

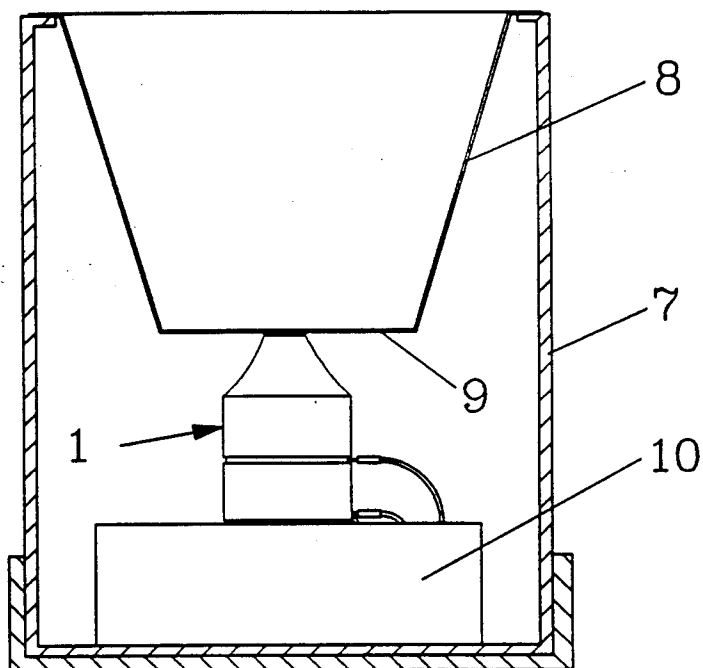


FIG. 2

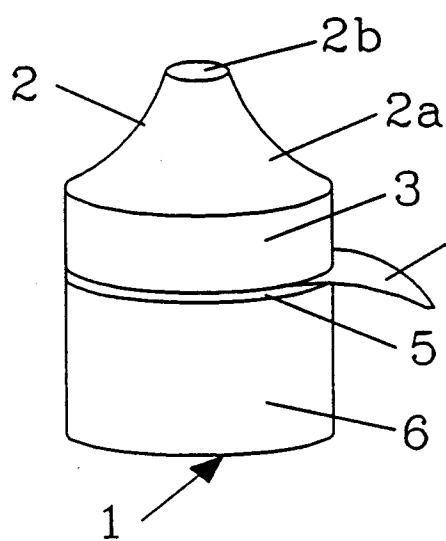


FIG. 3

