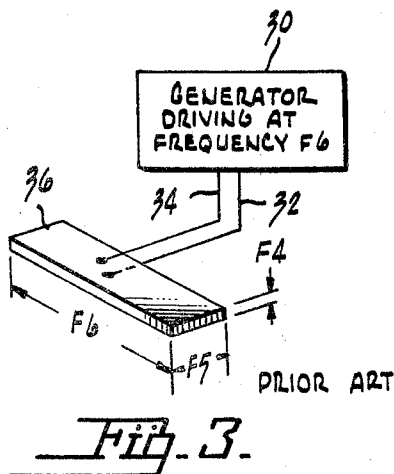
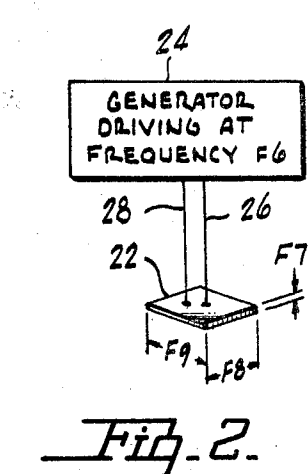
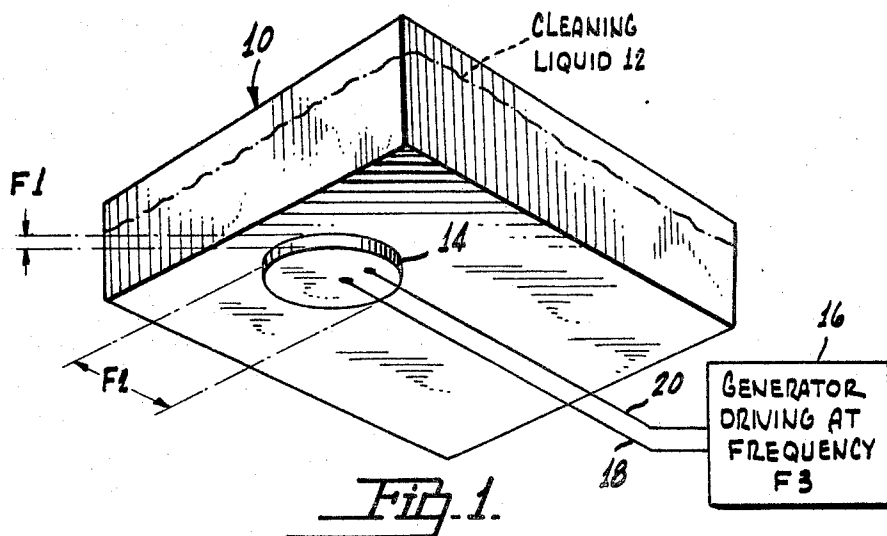


CROSS REFERENCE

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METHOD AND APPARATUS FOR RESONATING SMALL
PIEZOELECTRIC CRYSTALS AT LOW FREQUENCIES
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3,433,462

METHOD AND APPARATUS FOR RESONATING SMALL PIEZOELECTRIC CRYSTALS AT LOW FREQUENCIES

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6 Claims

ABSTRACT OF THE DISCLOSURE

A method of obtaining low frequency resonance of a piezoelectric crystal physically small in all dimensions. The crystal is excited by one or more frequencies, and at least one of those is determined according to either one or a family of secondary fundamental modes or resonances, found to occur in a crystal of this type. Excitation is at a frequency or frequencies at least one of which either corresponds to a secondary fundamental mode or modes, or alternatively, occurs in a family of such modes. In the latter event, the crystal resonates in a plurality of modes alternatively. The crystal may be either a natural (e.g. quartz) or a manufactured polycrystalline material, such as a ceramic.

CROSS REFERENCE TO RELATED APPLICATION

The present application is a continuation-in-part of my copending application Ser. No. 467,319 filed June 28, 1965 now Patent No. 3,371,233.

BACKGROUND OF THE INVENTION

Field of the invention

This invention pertains in general to the art of ultrasonics, in particular the art of applying an electrical field across a transducer or piezoelectric crystal associated with a cleaning tank, to translate the electrical field into wave energy transmitted through a cleaning liquid confined within the tank. The invention may thus be appropriately considered as relating to a system or method of resonating a piezoelectric device to obtain mechanical response thereof at one or more desired resonant frequencies.

Description of the prior art

In the field of ultrasonics, there are numerous applications involving the application of electrical wave energy to a crystal to resonate the crystal. For example, in ultrasonic cleaning one or more transducers (crystals) may be attached directly to the tank in which the article to be cleaned is immersed. The efficiency of the cleaning action depends largely on the range of frequencies in which the crystals are resonant, that is, the wider the band of frequencies, and the greater the number of the frequencies occurring in the said band, the more efficient the cleaning action. This is due to the fact that a typical article to be cleaned has parts, elements, or components differing widely in size and shape. In addition, said article will typically have openings, crevices, or cavities that are also widely variant in respect to configuration or size.

An element or crevice of the article to be cleaned is most effectively purged of foreign particles by wave energy occurring within a particular range of frequencies. As a rule of thumb, and at the risk of oversimplifying the description of the typical ultrasonic cleaning action, it may be said that loosening of foreign particles and contaminants of small crevices or areas is brought about

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most efficiently by wave energy in the higher frequency range. Larger, more open areas, conversely, are cleaned with particular effectiveness by low frequency energy.

Considering the wide variations in the sizes and shapes of areas to be cleaned, it is obvious that the greater the range of frequencies and the more frequencies that are applied within said range, the more effective will be the cleaning action. The problem, however, is that there is a relationship of frequency to crystal dimension, such that at least one dimension of a crystal must increase proportionately to lowering of the frequency at which the crystal is to be resonant.

Such increases in the crystal dimensions are undesirable on two counts. First, the increase in a crystal dimension may result in the crystal taking up an excessive amount of space in the ultrasonic cleaning equipment, especially upon the tank surface. And, secondly, any increase of a crystal dimension is accompanied by a substantial increase in the cost of the crystal.

Efforts have heretofore been made to solve this problem, as for example as shown in Mettler Patent No. 3,180,626 issued Apr. 27, 1965. That patent, however, provides only a partial solution to the problem, in that while teaching the vibration of thin crystals at low frequencies, the patent obtains this result only while keeping the crystal large in some other dimension thereof, as for example the diameter, or (if the crystal is non-circular), the length thereof.

SUMMARY

To overcome the problems noted above, I use a crystal that is small in every dimension thereof, and excite it at one or more frequencies, at least one of which drives the crystal at a secondary fundamental mode in which I have determined said crystals to be resonant, or alternatively, at a point intermediate a pair of secondary fundamental modes in which the crystal is found resonant. In either case, the selected secondary fundamental modes do not have the direct correspondence (heretofore thought essential) to one or more dimensions of the crystal.

While the invention could be used to obtain high frequency vibrations within the cleaning tank, its main value lies in its capability of producing vibratory energy of a low frequency, as for example 25 to 35 kHz., despite the fact that the crystal used is not only thin, but also is very small in all other dimensions thereof. Economies are thus realized that heretofore have not been thought capable of being achieved, since the smaller crystals are far less expensive than those at least one dimension of which is large. It is thus possible, in accordance with the invention, to utilize a small crystal in the application of one or more frequencies (which can be applied simultaneously) for energizing the mentioned secondary fundamental modes for obtaining high acoustical output at low frequencies.

BRIEF DESCRIPTION OF THE DRAWING

FIGURE 1 is a somewhat diagrammatic perspective view of an ultrasonic cleaning tank as seen from below, illustrating the invention;

FIGURE 2 is a somewhat diagrammatic perspective view showing the application of the invention to a rectangular crystal; and

FIGURE 3 is a view similar to FIGURE 2 showing a prior art crystal that would be required to obtain a frequency of a value approximately equivalent to that obtained with the crystal shown in FIGURE 2.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention may have general application in the field of ultrasonics. Purely by way of example, I have shown

it applied to an ultrasonic cleaning tank 10 holding a cleaning liquid 12. Attached to the bottom of the tank is a transducer or crystal 14. The location at which the crystal is attached is not critical. The crystal (there could be more than one) could be at the bottom or at the side of the tank. Also, it might merely be removably immersed in the tank, rather than affixed thereto.

At 16, I have diagrammatically illustrated an ultrasonic frequency generator having leads 18, 20 connected to crystal 14. The generator circuitry need not be specially designed, and could typically be either a half-wave or full-wave generator, having an oscillating circuit and tank coil. The frequency or frequencies of the oscillating circuit would be determined by the capacitance of the transducer and the inductance of the tank coil.

In FIGURE 1, crystal 14 is physically of small dimension both in thickness and diameter. Frequency F1 may be considered as a main frequency or mode, and has a correspondence with the thickness dimension. There is also another main frequency F2, corresponding to the diameter.

As brought out in detail in my copending application Ser. No. 467,319, and also in the Mettler Patent No. 3,180,626, the resonant frequency of the crystal is in inverse ratio to particular dimensions of the crystal. For example, as brought out in the Mettler patent, mechanical vibrations on the order of 25 kHz. would require a crystal dimension of approximately 4 inches. For a resonant frequency of 90 kHz., however, a crystal dimension of about 1 inch would be required. Low frequency resonance of the crystal is very desirable in devices of this type, it may be observed, in view of the particular adaptability for vibrations on this order to remove large, soft particles. Yet, the problem facing the manufacturers of ultrasonic cleaning equipment can be readily appreciated, when it is recognized that the cost of a crystal increases greatly with an increase in its size, and when it is further recognized that the cost of the high frequency generator arises along with the cost of the crystal, in view of the fact that the greater is the crystal dimension corresponding to the frequency applied, the greater must the electrical potential of the generator circuit be.

It has heretofore been considered that even in solutions to the problems such as have been offered in the above-referred to patent, at least one dimension of the crystal must remain large.

In accordance with the present invention, however, low resonant frequencies have been obtained in the crystal, using basically conventional generator circuits (that is, circuits in which the potential has not had to be increased), in association with crystals all dimensions of which are small.

The invention makes use of what may be termed secondary fundamental vibratory modes or frequencies in the transducer, the existence of which has been noted in copending application Ser. No. 467,319. The term "secondary fundamental modes" as used herein refers to resonances that do not have the direct correspondence with any crystal dimension equal to a half wave length. Any frequency, the wave length of which does have this particular relationship to one of the crystal dimensions, would be considered as a main frequency and heretofore it has been the common practice to apply such a frequency to the crystal for the purpose of creating the desired mechanical vibrations therein. Even in the Mettler patent referred to, the applied frequency has the above-specified correspondence with one of the crystal dimensions.

In any event, the further observation is made that the secondary fundamental modes are not predictable in the manner in which the art commonly determines modes or frequencies of vibratory crystal action, that is, by knowing the velocity of propagation of the wave within the crystal. Rather, the secondary fundamental modes seem to be dependent upon the crystalline structure and other subtle

parameters of the crystal, although by no means is it considered that this definitely and completely determines the value of the secondary modes.

Since the secondary fundamental modes or resonances cannot be mathematically computed or predicted in advance by reference to dimensions of the crystal, it becomes important to determine how, given a crystal of a particular size, one can determine what secondary fundamental modes exist therein. As to this, it has been found that assuming that a particular crystal is attached to a tank (as for example, a crystal as in FIGURE 1, the thickness and diameter of which are both small), one can shock-excite the crystal in the manner described in my copending application Ser. No. 467,319, and by doing so with a microphone placed in the tank one can detect the existence and value of those resonances capable of being defined as secondary to the main frequencies.

Or, other means can be used to ascertain the number and value of the secondary modes. For examples, one may drive the crystal in the ambient atmosphere, free of connections to a tank or other component. One would then drive the crystal by means of an impedance bridge, sweeping through a frequency range of 20 to 100 kHz., for example. An oscilloscope across the crystal output would provide a reading, in that when the crystal resonates in a secondary fundamental mode, there would be a larger, detectable resonance.

Once these resonances are known, it becomes possible to apply a selected frequency or frequencies, using a conventional half-wave or full-wave generator. This is selected to provide excitation of the crystal in regular use either at one of the secondary modes, or alternatively, at a point between two of the secondary modes.

Let it be assumed that a circular transducer or crystal has a diameter of one and one-half inches, and a thickness of .150 inch. The diameter corresponds to 53kHz., while the thickness corresponds to 530 kHz.

A crystal of these dimensions includes, in addition to the main frequencies corresponding to the dimensions set forth above, a second family of resonances (secondary fundamental modes) at 70 and 94 kHz., approximately, respectively. The crystal includes, further, a third family of resonances (also considered secondary fundamental modes) on the order of 25 and 35 kHz. respectively.

In such a case, one would drive the crystal at either 25 or 35 kHz., thereby obtaining low frequency resonance despite the fact that both dimensions are too small to obtain resonance at the specified low frequencies following practices heretofore employed in the art.

Basically, accordingly, the present invention encompasses first, the discovery that there are secondary fundamental vibratory modes in crystals; second, that although unpredictable, these modes can be found by detection through the use of appropriate instrumentation while applying to a crystal a frequency or frequencies that correspond in conventional fashion to a dimension of the crystal; and third, the application, in subsequent normal working use of the crystal, of a frequency or frequencies corresponding to one or more secondary resonances found in the crystal.

Referring to FIGURE 1, the application of the invention can now be readily perceived, when it is noted that the thickness dimension of crystal 14 corresponds to frequency F1, while the diameter of the crystal corresponds to frequency F2. Yet, the crystal is driven at a different frequency F3. Frequency F3 will be a frequency that is out of correspondence with any known frequency of the crystal, and instead corresponds with a secondary fundamental mode or resonance the existence of which in crystal 14, has been ascertained in the manner previously described herein. By driving the crystal at frequency F3 during regular use of the ultrasonic cleaning tank, one obtains the desired low frequency resonance despite the fact that both the thickness and diameter of the crystal are so small as to not

ordinarily be capable of producing said low frequency resonance.

The invention has equal adaptability in the driving of crystals that are other than circular in form. For example, in FIGURE 2, crystal 22 is rectangular, and has a thickness, width, and length all of which are small. By way of example, it can be considered that the greatest dimension of crystal 22 does not exceed 1½ inches.

Thus, ordinarily frequencies F7, F8, and F9 would correspond to the thickness, width, and length, respectively, of the crystal and would all be high frequencies.

A generator 24, connected by leads 26, 28 to the crystal, is, nevertheless, adapted to drive the crystal at a low frequency F6 not capable of being obtained in a crystal of small dimensions if ordinary, conventional practices are followed. The frequency F6 is determined in the manner described above with respect to the circular crystal, that is, by sensing the existence of secondary fundamental modes in the crystal while driving the same either by shock excitation or by steady state excitation at a frequency or frequencies known in advance as adapted to produce resonance of the crystal.

FIGURE 3 provides a view similar to FIGURE 2, but showing the prior art, thereby to permit a comparison between the prior art and the invention. In FIGURE 3, generator 30 is connected by leads 32, 34 to a rectangular crystal 36, having a thickness, width, and length corresponding to frequencies F4, F5, and F6. The length is considerable in FIGURE 3, and for example, might be on the order of about 4 inches in order to produce a low frequency, F6, of 25 kHz.

In these circumstances, generator 30 is required to drive the crystal at a frequency F6 in order to obtain low frequency vibration of the crystal. Yet, the crystal of FIGURE 2 is small in all its dimensions, while the crystal of FIGURE 3, though quite thin and narrow, must have a large longitudinal dimension.

The present invention, it should be noted at this point, goes beyond the basic principles thereof previously illustrated and described herein. It has been determined that by adjusting the driving frequency of generator 16 or 24 at a point lying somewhat between the highest and lowest of a family of the secondary fundamental modes found in the manner previously described, it becomes possible to vibrate the crystals in such fashion that its frequency output "jumps" or alternates between the several modes of the family. Thus, assuming the presence of secondary fundamental modes of 25 and 35 kHz. in a crystal, it becomes desirable to excite the crystal under normal working conditions at a frequency of 30 kHz. By so doing, the crystal resonates at times at 25 kHz., and at other times at 35 kHz. The division of time that the crystal vibrates at one or the other of these modes cannot be accurately predicted, and it is also not possible to predict whether, in a single cleaning cycle, resonance of the crystal will occur more at one of these modes than at the other. As indicated, there may be more than two modes in the family.

This, however, is no disadvantage, because though the operation of the equipment may be lacking in symmetry as regards driving the crystal at the specified low frequencies, the fact is that the oscillation between the specified two secondary fundamental modes is in fact predictable, and will occur with sufficient regularity during a single cleaning cycle to assure dislodging of particles of a size and consistency best acted upon by both of the secondary frequencies between which oscillation occurs.

One advantage of this characteristic resides in the obtaining of a plurality of frequencies within the cleaning tank. Such advantages have been discussed in detail in co-pending application Ser. No. 467,319 referred to above. This improves the cleaning action measurably.

There is, further, an insensitivity of the cavitation within the cleaning bath to any changes in temperature or depth of the liquid, or in the number of parts placed

within the liquid for cleaning. Heretofore, an essential element in all ultrasonic cleaning systems has been an automatic feedback control, which in other words can be defined as a means of sensing changes in the temperature or level of the cleaning liquid, and for adjusting the driving frequency according to the intelligence so obtained.

By driving the crystal at a frequency falling between previously detected secondary fundamental modes, criticality of temperature or liquid level can be dispensed with, thus in turn eliminating the necessity of an automatic feedback or frequency control.

A further discussion of this aspect of the invention may be appropriate. When one drives a crystal at a frequency corresponding to a particular physical dimension of the crystal, as in the Mettler patent or in any of the conventional prior art practices, the precise frequency at which the crystal is driven must correspond exactly to the resonance of the crystal. In this connection, the crystal resonance is known to change with each change of the liquid level and/or the liquid temperature. Such changes not only occur during and as a direct result of the cleaning of articles, but also, upon any changing of the particular type of liquid solution used.

Accordingly, in order to maintain the cleaning action at high efficiency, it becomes necessary to at all times drive the crystal at the precise resonant frequency corresponding to a crystal dimension, and as noted this changes and is dependent upon conditions within the cleaning tank. Hence the use of the feedback circuit, which detects such changes and which automatically changes the resonant output of the electronic generator to keep it in correspondence at all times with the true resonance of the crystal.

In practicing the present invention, such controls are not required, because by driving the crystal at a point between two secondary fundamental modes, the crystal resonance alternates between the two secondary fundamental modes, without requirement of outside controls either of an automatic or of a manual nature, and hence the crystal operates at all times at high efficiency.

As previously noted, further, complex, specially designed generator circuitry is not required, and a typical circuit usable in the manner described above can comprise either a half wave or a full wave generator with an oscillating circuit and tank coil. The frequency of the oscillating circuit is determined by the capacitance of the transducer or crystal, and the inductance of the tank coil. Since the capacitance of the crystal is at a fixed, always constant value, the frequency of the tank coil is adjusted so as to fall between two of the secondary fundamental modes previously sensed in the particular crystal. When this is done one has the advantage of a system that always operates at peak efficiency, regardless of the type of solution used, the depth thereof, the temperature of the solution, or any other extraneous conditions. And, very importantly, such results are achieved in a thin crystal that would also be small in its lateral dimensions.

It should be noted that in use, a plurality of frequencies could be applied to the crystal, whether the invention is applied by selecting a frequency coincident with a secondary fundamental mode, or alternatively, by selecting a frequency occurring between secondary fundamental modes.

For example, one might drive a crystal at a plurality of main frequencies corresponding with various dimensions of the crystal; at a frequency selected to coincide with one secondary mode; and at yet another frequency coincident with another secondary mode.

Or, one might drive only at a number of frequencies all of which coincide with secondary fundamental modes.

Then again, one might drive the crystal at one or more main frequencies; one or more frequencies coincident with (that is, occurring at) corresponding secondary modes; and one or more frequencies each of which lies between

two or more secondary modes to alternate resonance of the crystal therebetween.

A large variety of combinations of frequencies, main and secondary, or secondary alone, is thus possible. And, in every instance, the frequencies can be applied either simultaneously or not, whichever is desired. It is mainly important, so far as the present invention is concerned, that the crystal be resonated, in the manner described, in at least one secondary fundamental mode. Any recitation in the appended claims, therefore, of a frequency at which the crystal is to be driven, will therefore be understood as not being to the exclusion of any additional frequencies, whether they be main or secondary.

I claim:

1. In the generation of mechanical vibratory energy in a piezoelectric element, the method of obtaining resonance of said element in at least one frequency that is out of correspondence with the several dimensions of the element that includes the steps of:

(a) determining the existence and value of at least one secondary fundamental vibratory mode in said element; and

(b) thereafter driving the element at a frequency selected to resonate the same in said secondary fundamental mode.

2. The method of claim 1 wherein the frequency corresponding to said secondary mode is lower than any frequency having correspondence with a physical dimension of the piezoelectric element.

3. The method of claim 1, wherein the sensing step includes detection of a plurality of secondary modes, and wherein the subsequent driving of said element is at a frequency that lies between, and is effective to alternate resonance of the element between, the several secondary modes.

4. The method of claim 3, wherein said secondary modes are of frequencies lower than any frequency corresponding to a physical dimension of the element.

5. In an ultrasonic cleaning apparatus including a tank and a cleaning liquid within the tank, the improvement comprising:

(a) a piezoelectric element arranged to resonate at one or more vibratory modes effective to transmit wave energy through said liquid, and having a secondary fundamental vibratory mode out of correspondence with the several physical dimensions of said element; and

(b) a generator mounted in driving relation to said element and adjusted to drive the same at at least one frequency effective to resonate the element in said secondary mode.

6. In an ultrasonic cleaning apparatus, the improvement of claim 5 wherein said element includes a family of secondary fundamental modes, said generator being adjusted to a driving frequency lying between the highest and lowest modes of said family.

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