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Non-Uniform Ultrasonic Transducers for generating audio beams

Cross-related applications

The present application is related to a Singapore patent application entitled "Ultrasonic Transducers and amplifiers for generating audio beams", having
5 the same inventors, applicant and filing date as the present application.

Field of the invention

The present invention relates to ultrasonic transducers for generating a highly directed ultrasonic beam modulated with an audio signal, and which include an array of ultrasonic transducer elements.

10 Background of Invention

It is known that by transmitting an ultrasonic signal into air through an ultrasonic transducer, it is possible to produce a highly directional ultrasonic beam. Furthermore, if the ultrasonic beam is modulated with an audio signal
15 non-linear effects in the air will automatically demodulate the ultrasonic signal and regenerate the audio signal as the ultrasonic beam passes through the air [1][2]. This highly directional audio space is called an audio beam. This is a very promising technology with a very wide range of possible applications.

20 The basic configuration of an audio beam generation system is shown in Fig. 1. After the audio signal 1 is input to the system, it is first pre-processed by a unit 3 to reduce the distortion which is expected to be produced during the air-demodulation. Then it is modulated by a unit 5 onto an ultrasonic wave (e.g. 40 kHz) generated by an oscillator 7. The modulated wave is passed through
25 a power amplifier (e.g. a part of unit 5), and then fed to an ultrasonic transducer 9 and transmitted out to the air. In the air, the modulated signal is automatically demodulated by the non-linear effect of the air and the audible

sound is regenerated. The gradual regeneration of the audible sound is equivalent to having many virtual speakers in the air. The high directivity of the generated audible sound is the result of both the narrow ultrasonic beam and the virtual speakers along the path of wave propagation.

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Based on nonlinear acoustic theory, if a strong ultrasonic signal with two frequency components is transmitted to the air, the nonlinear effect of the sound propagation cannot be ignored. Due to this effect, a new sound signal will be generated with a frequency equal to the difference between the original
10 two frequencies. It was shown in [1] that for two primary ultrasonic sound fields $q_1(r, z)$ and $q_2(r, z)$ with frequency f_1 and f_2 respectively, due to the non-linearity of the air, the regenerated difference frequency signal (secondary signal) is:

$$15 \quad q_-(r, z) = -\frac{\pi\beta k_-}{\rho_0 c_0^2} \int_0^z \int_0^\infty q_1(r', z') q_2^*(r', z') G_-(r, z/r', z') r' dr' dz' \quad (1)$$

where r is the off propagation axis distance, z is the coordinate along the axis of the beam, k_- is the wave number of difference frequency $f_1 - f_2$ (assuming $f_1 > f_2$), β is the coefficient of nonlinearity, ρ_0 is the ambient
20 density of the medium, c_0 is the small-signal wave propagation speed, superscript $*$ signifies the complex conjugate, and $G_-(r, z)$ is a Green's function for difference frequency.

Based on Eqn. (1), it can be shown that the regenerated sound depends on
25 two factors:

1) the instantaneous strength of the primary waves. Assuming the sound pressure levels (SPL) of two primary waves are P_1 and P_2 respectively,

the strength of reproduced difference frequency signal will be P_- where $P_- \propto P_1 P_2$.

2) the primary sound field distribution, since Eqn. (1) includes a volume integration over the primary sound fields. Normally, the bigger the sound fields, the higher the regenerated sound SPL, provided that the phase differences of regenerated sound within the fields are small (e.g. $< \frac{\pi}{2}$).

Thus, a key component in such an audio beam system is the ultrasonic transducer (or emitter). Since the audible sound is regenerated from the ultrasonic beam which in turn is generated from the transducer, the ultrasonic transducer alone determines the sound field distribution of the ultrasonic beam. The configuration and performance of the ultrasonic transducer has a very big effect on the whole system's performance. It alone determines the directivity of the beam and the SPL of the ultrasonic field, and thus the regenerated audible sound field. The ultrasonic sound field (strength & phase) also influences the conversion efficiency with which the ultrasonic sound is converted into audio sound, the audible sound quality etc.

Various ultrasonic transducers for audio beam system have previously been proposed. A first kind of ultrasonic transducer uses many independent elements to form a transducer array [2]~[4]. The elements are normally commercial available PZT cells which are also used in other applications such as distance or intruder detections. A PZT cell can generate a big SPL for a relatively low driving voltage and has high electric-acoustic conversion efficiency since it uses PZT material.

An example of a known linear array of N elements is shown in Fig. 2. In the far field, the directivity of the beam is determined by following formula:

$$f(\theta) = \sum_{i=0}^{N-1} g_i a_i(\theta) \exp(-j \frac{2\pi d_i \sin(\theta)}{\lambda}) = a(\theta) g(\theta) \quad (2)$$

where $a_i(\theta)$ is i^{th} element's directivity (it is assumed that all elements are of same directivity), g_i is the driving signal amplitude of i^{th} element, d_i is the distance between i^{th} element and the reference element (denoted by $i = 0$), θ is the angle from the broadside, and λ is the wavelength of the ultrasonic wave. It is clear that the far field directivity is the product of each cell's directivity $a(\theta)$ and the array configuration factor $g(\theta)$. It can be shown that apart from the main beam which is transmitted at angle 0° (i.e. on the central axis of the transducer), if the distance between array elements is bigger than λ , there will be other big gate lobes in $g(\theta)$ within the range $\pm 90^\circ$. It can also be found that we can sharpen the directivity of the array by either sharpening each cell's directivity $a(\theta)$ or sharpening the array configuration factor $g(\theta)$.

Conventionally the cells are arranged in a uniform pattern, and all the cells are driven by the same signal. The cells are typically arranged close together to minimise the distance between the cells, and thereby to avoid gate lobes in the beam. Such conventional PZT cell arrays on uniform grids are shown in Fig. 3(a) and (b), with a substantially equal spacing between the neighbouring transducer cells (which are shown as the shaded circles). The appearance of a known PZT cell is shown in Fig. 4. It has 2 pins 6,8 which are attached respectively to positive and negative potential sources. The pins connect these sources electrically to portions of the PZT material which are spaced apart in the different polarization directions of the PZT material. Thus, the voltage of the pin 6 relative to that of the pin 8 is related to the deformation of the material.

A second kind of ultrasonic transducer employs a PVDF film [5]~[6]. In these arrays, PVDF films with electrodes on both sides are usually attached to fixed

substrates. Many small cells with specific resonant frequencies can be formed by providing cavities on the substrates. Normally only a single driving signal is applied to the whole transducer. A PVDF transducer has good properties (such as having a wide frequency band) and is low in cost. However, it needs
5 a high driving voltage, e.g. around 100Vpp. Also the electric-acoustic conversion efficiency is also lower than the transducers described above using a PZT array.

A third kind of ultrasonic array employs the electrostatic principle [7]~[9], and
10 movable diaphragms attached to substrates. This kind of array normally needs a high driving voltage and a high bias DC voltage. The electric-acoustic conversion efficiency is also low.

It is also proposed in [10] that a transducer can employ an array of elements
15 operated as a phase array. By controlling the phase and amplitude of each element in the array, the direction of the beam can be steered to desired directions without mechanically rotating the array. Unfortunately, this form of phase array is practically difficult to implement and is also high in cost.

20 Summary of the Invention

The present invention aims to provide a new and useful transducer array of the kind having many independent transducer cells.

In general terms, the present invention proposes that a transducer array is
25 formed having an array of transducer cells (such as PZT cells), which is not uniform, but instead consists of a plurality of uniform sub-arrays (which need not be identical with each other). There are normally more than 2 sub-arrays, such as at least 4 sub-arrays, or at least 9 sub-arrays.

By permitting the designer of a transducer array the freedom to design a non-uniform array, the present invention makes it possible to him to form a transducer having beam profiles which are not available with uniform transducer arrays.

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From a first point of view, the concept of a non-uniform array may be expressed as meaning that the array includes two or more sub-arrays, each of the sub-arrays (which need not be identical to each other) containing cells which are tightly placed together, and the various sub-arrays being spaced
10 apart from each other. More generally, this idea may be expressed by saying that the centres of the cells within one sub-array are arranged with a first spacing, but the sub-arrays are mutually spaced apart by a second spacing which is larger than the first spacing. In some cases, the distant between the sub-arrays can be very large such that the array can be viewed as an array
15 which generates multiple beams (i.e. there are only very small interactions between the respective beams from the sub-arrays). This possibility makes it possible for the array to generate a beam space large enough to cover many people in near range applications (i.e. 1 to 5 metres from the array).

20 Alternatively, or additionally, the concept of a "non-uniform" array may be expressed by saying that the plurality of sub-arrays (each having 4 or more cells) are such that the cells within each sub-array occupy all the points of a regular grid pattern spanning that sub-array, and the grid patterns for different neighbouring sub-arrays are not portions of a single regular grid pattern
25 spanning the two sub-arrays. Or, to express this idea in other words, each of the sub-arrays is associated with a respective regular grid pattern, and the grid patterns of neighbouring sub-arrays do not "match up" where those sub-arrays meet.

Note that, in one form of non-uniform array, there may be one or more sub-arrays where the cells are relatively sparse, and one or more other sub-arrays where they are relatively dense.

- 5 Some implementations the invention are sparse array configurations which scatter the positions of the gate lobes and thus reduce the level of these gate lobes. Such an array can also use fewer cells to form a large array aperture. That will increase the integration volume in the air where audible sound is regenerated, and thus increase the level of the regenerated audible sound
10 without increasing the amplitude of the ultrasound.

Note that the sub-arrays may each be of any shape, e.g., such that their outer profile is square, rectangular or round.

- 15 In some embodiments of the invention, some or all of the transducer cells (such as PZT cells) of the transducer array are provided with a "horn", that is an element defining a sound-transmission channel widening in the sound propagation direction.
- 20 The horn may increase the cell's directivity and SPL. It thus provides a way of using fewer cells in an array to achieve a desired ultrasonic SPL. In certain embodiments, it also provides a way to design a transducer array by balancing the position of the gate lobe and the single cell's gain in that position.

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A further possibility is that the array of transducer elements should not be exactly two-dimensional (i.e. flat), but should include transducer cells arranged such that their centres are in a three-dimensional configuration.

For example, the transducer array can be such that the transducers lie on a concave surface, or on a convex surface (these surfaces may be real, or alternatively notional; for example the surface may be defined as the convex hull of the transducers in the array). In the case, that the transducers lie on a concave surface, this may produce a narrower beam, with an increased ultrasonic SPL in the centre in the sound field. Conversely, in the case that the transducers lie on a convex surface, the main beam can be wider (e.g. to cover more people) and reduce the ultrasonic SPL (which in some applications is needed to reduce its harmful effect on the human body).

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In versions of the invention in which the transducer array is formed of uniform sub-arrays, the sub-arrays may be uniform as viewed in the direction facing towards the transducer (i.e. a view in which the flexing of the transducer array cannot be seen).

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In one possibility, all the cells of a given sub-array may be fed the same driver signal, but for each cell it is multiplied by a corresponding weighting coefficient for the corresponding sub-array of cells.

20 Conveniently, a single driver signal may be passed to a plurality of power amplifiers. Each power amplifier multiplies the driver signal by a respective weighting coefficient, and then transmits the result to each sub-array of transducer cells.

25 By using one, or a combination of more than one, of the above concepts, transducers and loudspeaker systems can be built which are useful for a wide range of specific applications.

The invention in its various aspects may be expressed as a transducer, 30 having an array of transducer elements, or as a loudspeaker system

comprising the transducer and also the circuitry for generating the signal input to the transducer. This circuitry may include units which respectively receive an input audio signal, pre-process it, and modulate it onto an ultrasonic signal. It may alternatively be expressed as a method of using such a loudspeaker
5 system to produce an audio beam, including, where appropriate, controlling the various degrees of freedom in the system (such as the weighting coefficients) to produce an audio beam with desired characteristics.

Brief Description of The Figures

Preferred features of the invention will now be described, for the sake of
10 illustration only, with reference to the following figures in which:

Fig. 1 is a block diagram of a known directional audio beam system;

Fig. 2 illustrates an example of a known linear array structure having many
15 cells;

Fig. 3 is composed of Fig. 3(a) and 3(b) which show conventional transducers having PZT elements arranged respectively in square and circular arrays which are tight and/or symmetric;
20

Fig. 4 shows a known PZT cell having two polarization pins, one positive, the other negative;

Fig. 5 is composed of Fig. 5(a) and Fig. 5(b), which respectively show a first
25 embodiment of the invention which is a transducer having a non-uniform array structure which is a sparse array in which the center part is more sparse than the edge part, and a second embodiment of the invention which is a transducer having a non-uniform array structure which is an array which consists of non-uniformly placed sub-arrays of tightly put cells;

Fig. 6 shows a possible transducer cell of a transducer array which is an embodiment of the present invention;

- 5 Fig. 7 is composed of Fig. 7(a) and 7(b) which are cross-sectional views of transducers which are embodiments of the present invention and comprise respectively a concave cell array and a convex cell array; and

Fig. 8 shows a transducer and an amplifier system which is a further
10 embodiment of the invention.

Detailed Description of the embodiments

- 15 Referring to Fig. 5(a), a transducer 21 which is an embodiment of the invention is shown. The transducer 21 is viewed looking towards a surface which carries a number of PZT elements 23.

In contrast to the known transducers of Fig. 3, the PZT elements 23 of the
20 transducers of Fig. 5(a) are arranged a non-uniform array. The transducer of 5(a) is non-uniform in that there are regions of the array (such as rectangular region 25, indicated by a dashed line) in which the density of the elements 23 is relatively high, and other regions (such as square region 27, indicated by a dashed line) in which it is relatively lower. We may say that in the region 25
25 the distance of each cell 23 to its nearest neighbouring cell is lower than in the region 27. Indeed, as illustrated, the cells 23 are packed tightly close together in the region 25, while in region 27 the cells are spaced apart by at least one cell diameter. As illustrated the high-density region 25 is proximate the edge of the array), while the cells 23 are relatively sparse in the region 27 in the
30 center of the array. In other embodiments, this is the other way around. Each

of the regions 25, 27 can be considered a sub-array of the whole transducer 21.

Note that within the region 25, the cells 23 are on all the points of a regular grid pattern which spans the region 25, while within the region 27 the cells 23 are on all the points of another regular grid pattern which spans the region 27 (these two grid patterns do not match at their edges, since the second grid pattern has a different unit cell size from the first grid pattern).

Another example of non-uniform array 31 is shown in Figure 5(b) in which the cells 33 are packed together tightly in sub-arrays 35,37 (indicated by dashed lines), and the sub-arrays 35, 37 are further from each other than the spacing of the cells 33 within the sub-arrays. Note that the sub-arrays 35, 37 are of different sizes, containing different numbers of cells 33. Within the sub-arrays 35, 37 the cells are arranged on all the points of a uniform grid pattern (a square mesh).

For the kind of arrays of cells in the transducers 21, 31 shown in Figs. 5(a) and 5(d), due to the non-equal distances between cells 23, 33, the positions of the gate lobes can be scattered in different angles and their strength will be greatly reduced. Another advantage of the arrays of cells in the transducers 21, 31 compared to known transducers is that a lower number of cells can be used to build an array having an aperture of a given size. A large aperture can be used to increase the integration volume as shown in Eqn. (1), thereby benefiting the regeneration of audible sound.

Turning to Fig. 6, a PZT cell is shown which can optionally be used in the transducers of Figs. 5(a) and 5(b). The PZT cell generally includes a structure 40 which is capable of generating ultrasonic air vibrations (and which may be identical to of the known PZT cell shown in Fig. 4), and additionally includes a

horn 41. By a horn is meant here an element defining a sound channel extending away from the sound-generation structure 40, and having a gradually increasing cross-sectional area in the direction away from the structure 40. Preferably, the horn 41 entirely encircles the channel (i.e. it preferably entirely surrounds an axis of the channel). The horn 41 may have a
5 frusto-conical shape, or alternatively a trumpet-shape.

By attaching the horn 41 to a known PZT cell, the cell's directivity $a(\theta)$ is greatly narrowed. The SPL of the cell of Fig. 6 is also greatly increased
10 compared to that of Fig. 4.

An embodiment of the invention may be formed which is a transducer in which some (or more preferably all) the PZT elements are provided with respective horns 41. Although the horns may require that the distance between the
15 centres of the cells is higher than in existing transducers, and thus make the gate lobes closer to 0° , a good balance can be achieved by properly designing the array configuration. Another advantage of the transducer, compared to a transducer formed using the known PZT cells of Fig. 4, is that it may achieve the same ultrasonic SPL despite having a lower number of
20 cells (or, if the number of cells is the same, achieve a higher SPL).

The transducer arrays of Figs. 5(a) and 5(b) are flat, i.e. the centres of all the cells lie on a common plane. However the invention is not limited in this respect. Specifically, Figs. 7(a) and 7(b) are schematic cross-sectional views
25 of two further transducers 42, 44 which are embodiments of the invention. These cross-sectional views are in planes passing through the centre of the corresponding transducer array. Looked at in the direction opposite to the sound propagation direction (which is the upward direction in Fig. 7(a) and 7(b)), the array of transducer elements looks just like that in Fig. 5(a).
30 However, in contrast to the transducer of Fig. 5(a), in the transducers 42, 44

the surfaces 46, 49 on which the transducer elements 48 are supported are not flat. Note that the views of Figs. 7(a) and 7(b) do not show the presence of the sub-arrays, but these would be visible if the transducers are viewed from the top of Fig. 7.

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As shown in Fig. 7(a), in transducer 42 the cells 48 are arranged along a concave curve. In fact, the front surface 46 of the transducer is concave in all directions, so that whichever plane through the transducer 42 is selected to produce the cross-sectional view, the surface 46 would appear concave. As shown in Fig. 7(b), in transducer 44 the cells 48 are arranged on a convex surface 49 (convex in all directions).

One choice of the curvature surfaces 46, 49 is a parabolic surface. The concave array of transducers 42 can be used to narrow the beam and to increase the ultrasonic SPL. The convex array of transducers 44 can be used to increase the beamwidth (which can be useful in some circumstances to increase the coverage area) and reduce the ultrasonic SPL (which is sometimes useful to reduce the harmful effects of ultrasonic waves on the human body).

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Fig. 8 illustrates a third embodiment of the invention, employing a transducer 31 of the kind shown in Fig. 5(b). Multiple power amplifiers 51 are provided, each receiving the same modulated signal (which may be the output of a modulation unit 5 of a loudspeaker system of the kind shown in Fig. 1). Each of the power amplifiers 51 multiplies the signal it receives by a (real, i.e. non-complex) weighting coefficient, and then outputs it to a respective set of cells, which may be all the cells of a single sub-array.

This arrangement may provide a "virtual sound centre", i.e. give the listener the impression that the sound is coming from a certain location in the array.

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This location may be different from any of the actual positions of the sub-arrays. For example, by appropriately controlling the power amplifiers 51 a signal can be supplied to four sub-arrays in the four respective corners of a rectangle, but the audible sound may be made to seem to be emitted from the
5 centre of the rectangle. This concept may be useful, for example, when the display is used as part of a big-screen displayer, in which the array of cells in the embodiment of Fig. 8 is located in aligned relation to (e.g. attached to the front or back of) the screen of a visual display device.

10 Note that this amplification system is much simpler than the phased array disclosed in [10] and discussed above, since in [10] the loudspeaker system not only tunes the amplitudes of the signals to the different elements, but also controls their phase (i.e. the amplitude multiplication factor applied to each signal is a complex number, not a real one). Doing this implies the need for
15 either a phase shifter or a time delay line. By contrast, the amplification system of the present invention may be much lower in cost, and easier to implement.

Although the invention has been explained above in relation to several
20 different embodiments, it is to be understood that the features of the embodiments may be combined in any desired combination. For example, the proposed cells having a horn may be used as some or all of the cells in the transducers of Figs. 5(a) or 5(b), and the arrangement of the cells of these transducers may be three-dimensional.

25

Furthermore, although the invention has been explained above in relation to PZT cells as the basic building element, the invention is not limited in this respect, and all aspects of the invention have application also in the cases that the ultrasound generating elements are of other forms, such as MEMS
30 structures built by depositing many PZT cells onto a substrate.

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Claims

1. A transducer comprising an array of transducer cells, the array consisting of a plurality of sub-arrays, the centres of the cells of the sub-arrays
5 being spaced apart with first spacing, and the sub-arrays being mutually spaced apart by a second spacing which is larger than the first spacing.
2. A transducer according to claim 1 in which the transducer cells of each of the sub-arrays are tightly packed together.
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3. A transducer comprising an array of transducer cells, the array consisting of a plurality of uniform sub-arrays each having 4 or more cells, the cells within each sub-array occupying all the points of a regular grid pattern spanning that sub-array, and the grid patterns for different neighbouring sub-
15 arrays not being portions of a single regular grid pattern spanning the two sub-arrays.
4. A transducer according to claim 3 in which the mutual spacing of the cells in one of the sub-arrays is different from the mutual spacing of the cells
20 in at least one of the other sub-arrays.
5. A transducer according to any preceding claim in which one or more of the transducer cells include:
an ultrasound generation element; and
25 a horn defining a channel and arranged for transmitting ultrasound generated by the ultrasound generation element along the channel, the channel widening in the sound propagation direction.
6. A transducer according to any preceding claim, in which the centres of
30 the transducer cells are not co-planar.

7. A transducer according to claim 6 in which the centres of the transducers lie on a concave surface.
- 5 8. A transducer according to claim 6 in which the centres of the transducers lie on a convex surface.
9. A transducer according to claim 7 or claim 8 in which the surface is a parabolic surface.
- 10 10. A combination of a transducer according to any preceding claim and an amplifier system, the amplifier system including a plurality of amplifiers, each amplifier being arranged to receive the same driver signal and to multiply it by a different real weighting coefficient, the outputs of the amplifiers
15 being transmitted to the cells of different sub-arrays.
11. A combination according to claim 10 including a control unit for controlling the amplifiers to control the weighting coefficients.
- 20 12. A combination according to claim 11 in which the control unit is arranged to control the amplifiers to generate a virtual sound emitting position which is different from the position of any of the sub-arrays.
13. A loudspeaker system comprising:
25 an input for receiving an audio frequency signal;
a pre-processing unit for receiving the audio signal, and pre-processing it to form a pre-processed audio frequency signal;
a modulation section for modulating an ultrasonic signal using the pre-processed audio frequency signal to generate a modulated ultrasonic signal;
30 and

a combination of a transducer and an amplifier system according to any of claim 10, claim 11 or claim 12.