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Ultrasonic Transducers and amplifiers for generating audio beams

Cross-related applications

The present application is related to a Singapore patent application entitled
"Non-Uniform Ultrasonic Transducers for generating audio beams", having the
5 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 transducers (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.

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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 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 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 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.

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 invention proposes that the cells of a transducer array are partitioned into two or more sets (with one or more cells per set), and that there is a different (real) weighting coefficient for each of the sets. All the cells are fed the same driver signal, but for each cell it is multiplied by a different weighting coefficient for each set of cells.

In a first possibility, the weighting coefficients may be just +1 or -1. In other words, certain cells are driven in anti-phase with other cells.

For example, suppose the cells are bi-polar cells, which each have a first
5 input pin and a second input pin, such that the outward deformation of the cell is determined by the voltage at the first pin minus the voltage at the second pin. In this case, the invention proposes that at any moment the voltage of the first pin minus the voltage of the second pin takes the same value for all cells of the first set of cells, and that it takes an equal and opposite value for all
10 cells of the second set of cells. This can be done just by connecting the pins of all the cells to circuitry which provides the same driver signals for each cell, but connecting the cells of the first set to that circuitry with a different polarity from that of the cells of the second set. Thus, the whole array may be driven by a single power amplifier.

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In other form of the invention, the number of sets of cells may be greater than two. In this case, 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 one of the sets of
20 transducer cells.

Optionally, the weighting coefficients may be chosen by analogy with 2-D time domain low pass filter coefficients. Appropriate selection of the amplitude factors makes it possible to achieve such beam properties as: an amplitude
25 profile in which the main beam has flat top; a rapid descent of pass band (i.e. the pass band has steep sides); and a low level of side-lobes. Also, the main beam width can be changed merely by changing the weighting coefficients.

In some embodiments of the invention, some or all of the transducer cells
30 (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.

5 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.

10 The array of transducer cells may be uniform (e.g. with the cells occupying all the points of a regular grid pattern, and/or with each cell having substantially the same distance to its nearest neighbour). Alternatively, the transducer cells may be arranged in a non-uniform pattern, comprising a plurality of uniform sub-arrays of cells.

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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 elements arranged such that their centres are in a three-dimensional configuration.

20 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
25 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).

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.

- 5 The invention in its various aspects may be expressed as a transducer, 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.
- 10 It may alternatively be expressed as a method of using such a loudspeaker 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

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

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

- 20 Fig. 2 illustrates an example of a known linear array structure having many 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 symmetric;
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Fig. 4 shows a known PZT cell having two polarization pins, one positive, the other negative;

Fig. 5 is transducer which is a first embodiment of the invention, including outer cells which are driven in anti-phase to the inner cells;

Fig. 6 shows the amplifier section and transducer of a loudspeaker system
5 which is a second embodiment of the invention;

Fig. 7 shows simulations of the beam shapes produced by the loudspeaker system of Fig.6;

10 Fig. 8 shows a possible transducer cell of a transducer array which is an embodiment of the present invention;

Fig. 9 is composed of Fig. 9(a) and Fig. 9(b), which respectively show a first example of non-uniform array structure which is a sparse array in which the
15 center part is more sparse than the edge part, and a second example of a non-uniform array structure which is an array which consists of non-uniformly placed groups of tightly put cells; and

Fig. 10 is composed of Fig. 10(a) and 10(b) which are cross-sectional views of
20 transducers which are embodiments of the present invention and comprise respectively a concave cell array and a convex cell array.

Detailed Description of the embodiments

25 Turning to Fig. 5, a transducer 20 is shown which is a first embodiment of the invention. The transducer 20 includes central PZT cells 21, which are all fed the same electric control signal by circuitry 23. The circuitry 23 feeds a certain electric signal to the cells 21. Let us suppose, for example, that the cells 21 are as shown in Fig. 4; in this case, the electric signal is applied between the
30 pins 6, 8 of the cells 21. The transducer 40 further includes outer PZT cells

25, which are all fed the same electric control signal by circuitry 47. However, the cells 25 receive the signal with the opposite polarity from the cells 41. In other words, the cells 21, 25 are connected to the respective set of circuitry 23, 25, such that when the voltage between the pin 6 and the pin 8 of the cells 21 is positive, the voltage between the pin 6 and the pin 8 of the cells 25 is of the same magnitude but negative. We may say that the pins of the cells 21 are positively connected, and the pins of the cells 25 are negatively connected.

Thus, the sound wave generated from a given cell is either in-phase with the electric signal, or 180° out-of-phase, depending on whether the cell is one of the inner cells 21 or outer cells 25. This means that, by properly designing the array configuration, the directivity and side-lobes of the array can also be improved. An advantage of the present ("bi-phase") transducer 20 is the simplicity with which it may be built and driven. Since the phase change is implemented by changing pin connections, a single driving signal can be used for all the cells. Therefore, a single power amplifier (of the kind which is included in unit 5 in Fig. 1) is enough to power the transducer 20.

The concept of controlling different ones of the cells signals with different amplitudes (in the case of Fig. 5, the amplitudes of signals fed to different respective sets of cells are opposite), can be generalised.

In particular, Fig. 6 shows a further embodiment of the invention in which signals of different (real) amplitudes are applied to different cells. A modulated signal (which may be the output of a modulation unit 5 of a loudspeaker system of the kind shown in Fig. 1), is transmitted into an amplification system 31 including multiple power amplifiers 32. The output of each of the power amplifiers 32 is input to a respective group of cells in the transducer 33. Thus, the cells of the transducer form an amplitude weighted array, in which the

signal amplitudes input to the respective cells are not all same. It is not just that at any time some of the signals may be positive and others negative, but that different ones of the cells which receive positive signals (or negative signals) are fed those signals multiplied by weighting coefficients which are different (real) numbers.

Based on time domain filter design theory, it is known that a two-dimensional (2-D) low pass filter can be designed based on a one-dimensional (1-D) filter by frequency transformation. By applying these 2-D filter coefficients as the weighting coefficients of the uniform transducer array, a spatial domain 2-D beam can be formed. Based on the correspondence between the time and spatial domains, this array has a 2-D beam shape similar to the time domain filter's 2-D frequency response.

The 2-D beam may be selected, for example, to include the feature that a diagram of the amplitude of the main beam in a range of angles has a flat top. Furthermore, it may be selected to have a low sidelobe and a rapid descent from the main beam to the sidelobe. These features are shown in Figs. 7(a) and 7(b), each of which is a computer-generated simulation of an amplitude profile which may be generated by a certain selection of the weights in the loudspeaker of Fig. 6. The horizontal axes indicate respective directions perpendicular to the direction in which sound propagates away from the transducer (in other words, these two directions are in the plane of the transducer's array of cells).

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These features are useful in many applications. For example, the flat top of main beam makes it possible for the beam to cover uniformly many people in positions intersecting with the beam. That is, people within the beam will hear the same level of SPL, even though they are in different respective positions. Furthermore, people will also feel an abrupt change in SPL when going from

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inside of the main beam to outside of it, due to the rapid descent of the pass band and the low side-lobe. Thus the array can be used to build a perfect isolated sound space.

- 5 Another advantage of this embodiment of the invention is that the main beam width can be changed electrically by changing the weights. As shown in Fig. 7(a), with one set of weighting coefficients the beam is relatively narrow. Conversely, as shown in Fig. 7(b), the beam is wider. Thus, by changing the weighting coefficients of the array cells, the main beam can be changed from
10 a narrow beam in Fig. 7(a) to a wider beam in Fig. 7(b) without changing the structure of the transducer.

Note that the amplification system 31 of Fig. 6 is much simpler than the phased array disclosed in [10] and discussed above, since in [10] the
15 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 either a phase shifter or a time delay line. By contrast, the amplification system of the present invention may be much
20 lower in cost, and easier to implement.

Note also the purpose of the phase array in [10] is to steer the beam in a desired direction, whereas in the present embodiment the amplitude weighted array is used to form a beam with a good shape (amplitude profile). Thus, the
25 methods of designing the weighting amplitudes are also different..

Due to symmetries in the 2-D filter coefficients, the amplitude signal produced by a given one of the power amplifiers 32 can be transmitted to a plurality of cells, which form a group of cells. Therefore, a single power amplifier 32 can
30 drive this group of cells. The transducer includes circuitry for transmitting the

outputs of the power amplifiers 32 to each cell of the respective group of cells. For example, only 10 power amplifiers are needed to drive the 7×7 array as shown in Figure 6.

5 Turning to Fig. 8, a PZT cell is shown which may be used in some embodiments of the invention. 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
 10 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 frusto-conical shape, or alternatively a trumpet-shape.

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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. 8 is also greatly increased compared to that of Fig. 4.

20 Embodiments of the inventions may be formed in which some (or more preferably all) the transducer cells of the transducer are provided with respective horns 41. Although the horns may require that the distance between the 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
 25 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 cells (or, if the number of cells is the same, achieve a higher SPL).

Turning to Fig. 9(a), a transducer 51 is illustrated which may be used in the embodiments of the invention shown in Fig. 5 or Fig. 6. The transducer 51 is viewed looking towards a surface which carries a number of PZT elements 53.

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In contrast to the known transducers of Fig. 3, the PCT elements 53 of the transducers of Fig. 9(a) are arranged a non-uniform array. The transducer of 9(a) is non-uniform in that there are regions of the array (such as region 55, indicated by a dashed line) in which the density of the elements 53 is high, and other regions (such as region 57, indicated by a dashed line) in which it is low. In the region 57, the array is sparse, i.e. the cells are not as tightly put together as they are in the region 55. We may say that in the region 55 the distance of each cell 53 to its nearest neighbouring cell is lower than in the region 57. Indeed, as illustrated, the cells 53 may be tightly close together in the region 55. As illustrated the region 55 is proximate the edge of the array), while the cells 53 are sparse in the region 57, in the center of the array. In other embodiments, this is the other way around. Note that within the region 55, the cells 53 are on all the points of a regular grid pattern, while within the region 57 the cells 53 are on all the points of another regular grid pattern (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 61 is shown in Figure 9(b) in which the cells 63 are put tightly in groups 65,67 (indicated by dashed lines), and the groups 65, 77 are further apart from each other than the spacing of the cells 63 within the groups. Note that the groups 65, 67 are of different sizes, containing different numbers of cells 63. Within the groups 65, 67 the cells are arranged on all the points of a regular grid pattern (a square mesh). Each of the regions 55, 57, 65, 67 can be considered a sub-array of the respective transducer.

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For the kind of arrays of cells in the transducers 51, 61 shown in Figs. 9(a) and 9(d), due to the non-equal distances between cells 53, 63, 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 51, 51 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.

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Figs. 10(a) and 10(b) are schematic cross-sectional views of two further transducers 72, 74 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. 10(a) and 10(b)), the array of transducer elements looks just like that in Fig. 3(a). However, in contrast to the known transducer of Fig. 3(a), in the transducers 72, 74 the surfaces 76, 79 on which the transducer elements 78 are supported are not flat.

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As shown in Fig. 10(a), in transducer 72 the cells 78 are arranged along a concave curve. In fact, the front surface 76 of the transducer is concave in all directions, so that whichever plane through the transducer 72 is selected to produce the cross-sectional view, the surface 76 would appear concave. As shown in Fig. 10(b), in transducer 74 the cells 78 are arranged on a convex surface 79 (convex in all directions).

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One choice of the curvature surfaces 76, 79 is a parabolic surface. The concave array of transducers 72 can be used to narrow the beam and to increase the ultrasonic SPL. The convex array of transducers 74 can be used to increase the beamwidth (which can be useful in some circumstances to

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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).

- 5 Although the invention has been explained above in relation to several different embodiments, it is to be understood that the features of the embodiments may be combined in any desired combination. For example, the transducers of Figs. 5 or 6 may both use the proposed cells having a horn, and have a three-dimensional configuration as shown in Figs. 10(a) and
10 10(b).

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
15 that the ultrasound generating elements are of other forms, such as MEMS structures built by depositing many PZT cells onto a substrate.

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Claims

1. A combination of a transducer and an amplifier system, the transducer having:

5 an array of transducer cells, the cells being partitioned into two or more sets,

for each set of cells, a respective set of signal transmission circuitry for supplying the cells of that set with a corresponding electric signal; and

the amplifier system including a plurality of amplifiers, each amplifier
10 being arranged to receive the same driver signal and to multiply it by a different real weighting coefficient, the outputs of the amplifiers being transmitted to different respective ones of the sets of signal transmission circuitry.

15 2. A combination according to claim 1 including a control unit for controlling the amplifiers to control the weighting coefficients.

3. A transducer having an array of transducer cells, each transducer cell having a first input pin and a second input pin, the outward deformation of the
20 cell being determined by the voltage at the first pin minus the voltage at the second pin,

the cells being divided into two groups, the cells of the first group being connected to receive a driver signal with a first polarity and the cells of the second group being connected to receive the driver signal with the opposite
25 polarity.

4. A transducer according to claim 3 in which the first group of cells are located at a central portion of the array, and the second group of cells are located at a peripheral portion of the array.

5. A combination of a transducer according to claim 3 or claim 4 and an amplifier system for generating the driver signal, the combination including circuitry for supplying the driver signal to the cells of the first and second groups.

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6. A combination according to any of claims 1, 2 or 5 in which each transducer cell includes:

an ultrasound generation element; and

10 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.

7. A combination according to any of claims 1, 2, 5 or 6 in which the transducer cells are arranged in a non-uniform pattern, comprising a plurality
15 of uniform sub-arrays of cells.

8. A combination according to any of claims 1, 2 or 5 to 7 in which the centres of the transducer cells are not co-planar.

20 9. A combination according to claim 8 in which the centres of the transducers lie on a concave surface.

10. A combination according to claim 8 in which the centres of the transducers lie on a convex surface.

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11. A transducer according to claim 9 or claim 10 in which the surface is a parabolic surface.

12. A loudspeaker system comprising:
30 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;

5 and

a combination of a transducer and an amplifier system according to any of claims 1 or 2 or any of claims 5 to 11.

13. A method of operating a loudspeaker system according to claim 12, in
10 which the combination of the transducer and amplifier system is according to claim 2, the method including modifying the weighting coefficients to modify the profile of an audio beam generated by the transducer.