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Parametric Speaker and Parametric Speaker System

Field of the invention

The present invention relates to a speaker for generating ultrasonic sound, which may be modulated using an audio frequency. The invention further
5 provides a speaker system comprising at least one speaker and an amplifier system.

Background of Invention

It is well-known that an ultrasonic transducer array (that is, an array
10 composed of a plurality of elements, each of which is capable, under the control of an applied electronic signal, of transmitting an ultrasonic signal into air) can produce a narrow ultrasonic sound beam. It is further known to AM modulate the ultrasonic sound beam using an audio signal, by using the audio signal to modulate the electronic signals which drive the ultrasonic transducer
15 array. The AM modulated ultrasonic beam is spontaneously demodulated as the beam propagates through the air because of the non-linear acoustic effects of air, so as to generate an audible sound corresponding to the input audio signal. So called "parametric speakers" are ultrasonic speakers which use this phenomenon to produce a sound spotlight that is audible only by
20 people at the location of the sound spotlight.

Fig. 1 illustrates the ultrasonic sound profile generated by a plurality of transducer elements 1 in a known transducer array (for simplicity, only a single row of transducer elements is shown, but it is to be understood that this
25 may be just one row of a two-dimensional array, which extends also in the direction perpendicular to the page). The elements 1 are spaced apart by a distance d . Now, recall Huygens' principle, which states that every point on a primary wavefront serves as the source of spherical secondary wavelets 3

such that the primary wavefront at some later time is the envelope of these wavelets. Huygens' principle accordingly implies that the envelope of the secondary wavelets gets closer to the shape of a planar wavefront as the center-to-center transducer distance d gets smaller. In fact, it is well-known
 5 from the theory of waves that a very narrow sound beam can be produced by an ultrasonic transducer array with a center-to-center distance d of less than the wavelength of the ultrasound. Unlike the spherical wave, the plane wave propagates straight ahead without spreading out, thereby making the wave distribution more localized, that is more directed. In fact, it can be proven that
 10 when d is smaller than the wavelength of the ultrasonic waves transmitted out of a planar transducer array, for example, only the zero-order principal sound peak exists, corresponding to the direction perpendicular to the array surface.

Fig. 2 shows the known transducer array of Fig. 1 seen from the front (i.e.
 15 looking towards the transducer along the propagation direction of the sound beam). As can be seen from Fig. 2, in a typical ultrasonic transducer array of a known type the transducer elements 1 may be circular and are arranged on a planar substrate 5. The transducers 1 may be piezoelectric, for example lead zirconate titanate (PZT) bimorph type. The transducers are typically
 20 driven in-phase by amplifier circuitry (not shown). The ultrasonic transducers 1 are mounted adjacent to one another in a regular lattice format with a center-to-center separation d that is greater than the wavelength of the ultrasonic waves.

25 Unfortunately, piezoelectric bimorph type ultrasonic transducers are difficult to pack close together because of their fairly large size, typically from 1 cm to 4 cm in diameter. When attempting to assemble them into an array, it is extremely difficult to provide the desired less-than wavelength spacing between two adjacent neighbors due to the physical constraint that the

wavelength of an ultrasonic wave is so small in the order of millimeters, for example, 8.6 mm for a 40 kHz signal.

5 In order to realize an inter-element spacing less than the wavelength, the ultrasonic transducers would have to be very small and separated by only a very short distance.

Summary of the Invention

10 The present invention aims to provide a new and useful parametric speaker, and a new and useful parametric speaker system comprising a speaker and an amplifier system.

15 In general terms, the present invention proposes an ultrasonic speaker in which a plurality of transducer elements are arranged to generate ultrasonic signals which converge onto a reflective surface, and that the reflective surface reflects the signals to generate respective reflected ultrasonic signals. The reflected ultrasonic signals have a spacing which is less than the spacing of the transducer elements.

20 Thus, the present invention makes it possible to provide a speaker in which ultrasonic sound generation employs conventional transducers, and yet the spacing of the transmitted ultrasonic signals is not limited by size and/or separation of the transducers.

25 In one form, the reflective surface is a curved surface. For example it may be a curved surface defined by an axis, and in this case the curved surface may substantially entirely encircle the axis. For example may be a conical surface, or a cone-like surface (e.g. a trumpet shape), defined based on an axis. In this case, the ultrasonic elements may be arranged around the axis of the conical surface. One possibility (in particular if the reflective surface entirely encircles

the axis) is for the ultrasonic elements to be spaced out around substantially the entire axis.

Conveniently, the ultrasonic elements may be arranged on a support base member, which may be a cylindrical (tubular) member having an inwardly-directed cylindrical surface encircling a longitudinal axis. The transducer
5 elements may be located on the inwardly-directed surface, and the longitudinal axis may coincide with the axis of the conical surface.

The reflected ultrasonic signals may be parallel. Alternatively they may be approximately parallel, but having a degree of convergence (i.e. they become
10 focused) or divergence as they propagate away from the speaker. For example, the reflected signals may propagate in a respective direction which is a few degrees away from a normal direction to the speaker (e.g. the axis of the curved surface).

In preferred arrangements, the speaker is used with a pre-processing unit
15 (and normally an amplifier system which may be integrated with the pre-processing unit) which generates one or more control signals for the transducer elements at an high ultrasonic frequency such that the inter-element spacing (i.e. the distance between the centres of adjacent elements of the array) of the transducers is higher than the ultrasonic wavelength, and
20 yet the spacing of the adjacent reflected signals is less than the wavelength of the ultrasonic waves.

Brief Description of The Figures

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

25 Fig. 1 illustrates how, in a known transducer array, a planar wavefront tends to be formed as the distance between adjacent transducer elements decreases;

Fig. 2 is a front view of a known ultrasonic transducer array;

Fig. 3 is composed of Figs. 3(a) and 3(b) which show respectively (a) an assembly view and (b) an exploded view, of a parametric speaker which is embodiment of the present invention and which includes a cylindrical support
5 base and a conoidal reflector;

Fig. 4 is a schematic cross-sectional diagram of the embodiment of Fig. 3, and illustrates typical ultrasonic beam paths in the embodiment of Fig.3;

Fig. 5 is a schematic diagram of a view towards the embodiment of Fig. 3, and further illustrates typical ultrasonic beam paths in the embodiment
10 of Fig. 3;

Fig. 6 illustrates the relationship between the reflector's inclination angle and beam centres on the reflector; and

Fig. 7 is a computer-generated simulation of the 3-D directivity of the embodiment of Fig. 3 in the case that the embodiment has a 33 degree
15 reflector, the simulation illustrating the sound amplitude 0.5m from the surface of the speaker.

Detailed Description of the embodiments

20 Referring firstly to Fig. 3, an embodiment of the invention is shown in a perspective view (Fig. 3(a)) and an exploded view (Fig. 3(b)). The embodiment is a speaker. A pre-processing unit (not shown) is provided for modulating an audio-frequency signal onto an ultrasonic signal to form an amplitude modulated ultrasonic control signal which is fed to the speaker by
25 circuitry (not shown), and typically also via an amplifier unit.

The speaker includes a cylindrical support base 13 having a longitudinal axis of longitudinal symmetry, and a central open section. The speaker further includes a regular transducer array consisting of a plurality of ultrasonic
30 transducers 11 (typically piezoelectric bimorph type ultrasonic transducers)

mounted adjacent to one another on the inwardly-directed cylindrical surface of the cylindrical support base 13. The respective transmission axis each transducer 11 points towards the longitudinal axis of the support base 13.

- 5 The transducers 11 are arranged in respective rings, encircling the longitudinal axis of the support base 13, with each of the rings being composed of a group of transducers 11 at the same distance along the longitudinal axis. There may be any number of rings (even just one), but typically there are at least two rings (as shown in Fig. 3(b)), or at least three
- 10 rings. In the case that there are plural rings, each of transducers 11 may be in angular register, around the longitudinal axis of the support base 13, with respective transducers 11 in each of the other rings. Thus, a typical transducer 11 has four nearest neighbours: the two transducers to either side of it within the same ring, and two transducers in corresponding angular
- 15 positions within the two adjacent rings.

The speaker further includes a solid reflector 15 having a curved reflector surface for reflecting ultrasonic beams which impact it. The curved surface may be a conical surface (note that the term "conical surface" is used in this

20 document to any surface which has a portion conforming to the conventional equation for a cone; thus, a reflective surface of the solid reflector 15 which is frusto-conical is included within the meaning of the term "conical surface"). The reflector 15 is positioned so that its centre line coincides with the longitudinal axis of the support base 13.

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The cylindrical support base 13 is encircled by a tube-shaped outer cover 17, and a top cover 19 and a bottom cover 20 are provided at opposite ends of the longitudinal axis of the support base 13. The top cover 19 has a central

circular aperture through which the ultrasound beam propagates away from the speaker.

Turning to Fig. 4, a cross-sectional view of the speaker of Fig. 3 is shown schematically, in a plane including the longitudinal axis of the support base 13 (which is the vertical direction in Fig. 4) and two transducers 11 of the same ring (the transducers 11 of other rings are not shown) on opposite sides of the longitudinal axis. The function of the reflector 15 is to reflect AM modulated beams 23 emitted by the transducers 11 towards the longitudinal axis of the support base 13. This beams 23 are reflected through an L-bend, to form upwardly propagating beams 25 as shown in Fig.4. The angle between the original propagation direction of the beams 23 and the sloping sides of the reflector 13 is denoted by α . By varying the value of α , the reflected beam pattern can be adjustable. When $\alpha < 45^\circ$, the beam tends to be focused, while $\alpha > 45^\circ$, the beam tends to be dispersed.

Turning to Fig. 5, a view is shown looking towards the speaker along the longitudinal axis of the support base 13. The figure shows two adjacent transducers 11 in the same ring. These transducers have a centre-to-centre distance of d . Each transducer generates a beam 23 which impacts the reflector 13 at a respective location (termed here a "beam centre") on the reflector 15. The beam centres are indicated as C and D in Fig. 5. Note that the center-to-center distance d' of reflective beam centers C, D on the reflector 13 is smaller than the spacing d of the transducers 11 themselves owing to the fact that each transducer 11 is mounted on the wall so that its axis of propagation points towards the longitudinal axis of the cylindrical support base 13. The center-to-center distance d' of beam centers C, D on the reflector 15 can thus be made smaller than the wavelength of the ultrasonic waves by appropriately choosing the value of R , which denotes the

ratio of the radius of the inner surface of the support base 13 and the radius of the reflective surface of the reflector 15 at the point along the longitudinal axis of the support base 13 at which the beams 23 impact it. From beam centres C, D onwards, the AM modulated reflected beams 25 (not shown on Fig. 5) propagate parallel to the shared longitudinal axis of the support base 13 and the reflector 15, with a center-to-center distance d' scaled down from d by a factor of R .

Turning now to Fig. 6, the case is illustrated in which there is more than one ring of transducers on the inwardly-facing wall of the support base 13. Let us consider the AM modulated ultrasonic beams emitted by transducers 11a, 11b which are displaced from each other parallel to the longitudinal axis of the support base 13 (i.e. they are in angular register around this axis). The beams 23a, 23b emitted by each of the transducers 11a, 11b impact the reflector 13 at respective beam centres. The center-to-center distance d'' between beam centers of beams 23a, 23b emitted by the transducers 11a, 11b is determined by the inclination angle α of the reflector, as shown in Fig. 6. With an increasing α , the d'' will be decreased.

Note that the total distance travelled by the beams 23a, 23b before reaching the top of Fig. 6 is different, because the beam 23b has a much shorter distance to go in the vertical direction. Therefore, if the transducers 11a, 11b are in phase, then the beams 23a, 23b will not be quite in phase when they reach the top of Fig. 6. Optionally, an amplifier plus a phase delay circuit (e.g. also within the amplifier unit) may be used to compensate this difference. For example, a single amplifier is used to generate a control signal to drive one ring of transducer elements, and the output from the amplifier can be passed to the phase delay circuit to generate a control signal to drive the other ring. The phase delay may be chosen to ensure that the reflected ultrasonic signals

are in phase. More generally, when there are more than two rings, they may be more than one phase delay circuit.

Fig. 7 shows a result of a numerical simulation of an arrangement as shown in Fig. 3. The simulation used two rings of transducers, each with 25 transducer elements (so 50 transducer elements in total). The value of d was chosen to be 8.6mm, and α was chosen to be 90 degrees minus 33 degrees (i.e. 57 degrees). It will be apparent from Fig. 7 that the present embodiment can indeed attain a main lobe with a desirable narrow width, side lobes having a high enough attenuation with respect to attenuation at the main lobe.

Although only a single embodiment of the invention has been illustrated in detail, many variations of the embodiment are possible within the scope of the invention, as will be clear to a skilled reader. For example, while, as described above, a conical reflector surface is convenient for use in the invention, it is possible to implement the invention using other surfaces, particularly other curved surfaces. For example, the curved surface may be another surface defined by an axis, such as a trumpet shaped surface (i.e. a surface which encircles the axis, which each of the cross-sections through the surface being circular, the radius of the circles being a non-linear monotonic function of the distance along the axis).

Furthermore, in some arrangements, the curved surface need not necessarily encircle the entire axis, but may, for example, only subtend about 180° or 90° of angles around the axis. In this case the reflective elements also may be provided only in locations on a single side of the axis.

Claims

1. An ultrasonic speaker comprising:
 - a reflector having a reflector surface; and
 - a plurality of ultrasonic transducer elements, arranged to transmit
5 respective ultrasonic signals towards the reflector surface;
 - the reflector and ultrasonic transducer elements being arranged so that
the ultrasonic signals intercept the reflector surface; and
 - the reflector surface being shaped and arranged to reflect the
ultrasonic signals to form respective reflected ultrasonic signals having a
10 nearest-neighbour spacing which is less than the nearest-neighbour spacing
of the ultrasonic transducer elements.
2. A speaker according to claim 1 in which the reflector surface is a
curved surface defined by an axis.
3. A speaker according to claim 2 in which the reflector surface is a
15 conical surface around a longitudinal axis, the ultrasonic transducer elements
being arranged around the axis.
4. A speaker according to claim 1, claim 2 or claim 3 in which the reflector
surface is shaped and arranged so the reflected signals share a common
propagation direction.
- 20 5. A speaker according to claim 1, claim 2 or claim 3 in which the reflector
surface is shaped and arranged so the reflected signals converge as they
propagate.
6. A speaker according to claim 2 in which the ultrasonic transducer
elements are arranged in groups, each group of transducer elements

comprising multiple ones of the ultrasonic transducer elements located at the same respective position along the longitudinal axis.

7. A speaker according to any preceding claim in which the plurality of ultrasonic transducer elements are located on an inwardly directed surface of
5 a cylindrical support base.

8. An ultrasonic speaker comprising:

a reflector having a curved surface defined by an axis; and

a plurality of ultrasonic transducer elements arranged around the axis to transmit respective ultrasonic signals towards the reflector surface;

10 whereby the ultrasonic signals are reflected at respective locations on the curved surface to form respective reflected ultrasonic signals having a nearest-neighbour spacing which is less than the nearest-neighbour spacing of the corresponding ultrasonic transducer elements..

9. A speaker according to any preceding claim in which the ultrasonic
15 transducer elements are piezoelectric elements.

10. A parametric speaker system comprising:

a speaker according to any preceding claim;

a pre-processing unit for modulating an audio-frequency signal onto an ultrasonic signal to form an amplitude modulated ultrasonic control signal; and

20 circuitry to transmit the modulated ultrasonic control signal to the plurality of ultrasonic transducer elements.