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A Highly-Directional Sound Projection System

Field of the invention

The present invention relates to a parametric speaker, and a sound generation system including the parametric speaker.

- 5 The application is related to Singapore patent application 200300490-0, which was not published at the priority date/filing date of the present application.

Background of Invention

There is no doubt that it would be desirable to be able to produce a narrow beam of audio-frequency sound waves. WO01/23104A2 describes a system
10 which does this, by replicating an input signal many times, modifying each version of the signal slightly, and feeding each version into a respective loudspeaker element to produce a desired sound field (namely a narrow, focused beam). Unfortunately, such a system is likely to prove expensive to manufacture.

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Another solution is to use parametric speakers, that is to say speakers which generate ultrasonic waves. The principle of a known parametric speaker system is illustrated in Fig. 1(a). An audio signal 1 (which may be obtained from a microphone (not shown) or another audio electronic device such as a
20 DVD player (not shown)) is input from the left of the figure to a signal processing unit 2. In the signal processing unit 2 it is pre-processed by a pre-processing unit 3, and then used by a multiplier unit 5 to modulate an ultrasonic signal produced by an ultrasonic oscillator 7 which produces vibrations at a single frequency in the ultrasonic range. The result is
25 transmitted to a power amplifier 9, and from there to a parametric speaker 11. Let us assume that the speaker 11 emits two ultrasonic waves with frequencies f_1 and f_2 . Since the ultrasonic waves have a short wavelength,

the output field of the speaker 11 can be focused into a narrow beam. The ultrasonic waves have a non-linear interaction with the air, and this generates sound waves having tones f_1+f_2 (an inaudible high frequency component) and f_1-f_2 (a difference signal which may be in the audio range). The system is
 5 designed such that this difference frequency corresponds to the frequency of the audio signal 1 input to the left of Fig. 1(a). In other words, the non-linear effects of the propagation of the ultrasonic wave in the air cause a demodulation, which in turn generates the desired audio sound in a narrow beam.

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More generally, if the audio signal 1 contains multiple audio frequency components of differing amplitudes, then the pre-processor unit 3 aims to operate such that these amplitudes are equal to the corresponding amplitudes of the audio frequency signals produced by the air-demodulation of the
 15 ultrasonic wave. Thus, a parametric speaker provides an alternative way of providing audible sound radiation in a narrow beam. If the bandwidth of the parametric speaker is sufficiently great, the difference frequency f_1-f_2 can be arranged to be within any of the low, middle and high audio frequency ranges.

20 The Berklay's far-field solution, which is well-known in this field, predicts that the demodulated secondary waveform along the axis of the beam is proportional to the second time derivative of the square of the modulation envelope. The secondary wave is therefore generated with high levels of harmonic distortion. One known method of designing the system of Fig. 1(a)
 25 to minimise this is illustrated in Fig. 1(b). In this system an input audio signal, written as $x(t)$, is twice integrated by a double integration unit 13, then a unit 15 multiplies it by a gain m and adds an offset. The result is input to a square-root unit 17. This resultant signal $E(t)$ is used by a unit 19 to modulate an ultrasonic signal f_c obtained from the crystal oscillator 7, to produce a signal
 30 $E(t)\sin(2\pi f_c t)$ which is transmitted by the parametric speaker 11. This is

subject to a double derivative operation due to the non-linear effects of the air, to produce a demodulated signal $y(t)$. The result is that $y(t) \propto x(t)$.

It should be noted that the square root operation performed by the unit 17 would, if performed perfectly, introduce infinite harmonics of the input signal $x(t)$, so that in principle a source with infinite bandwidth is required to achieve $y(t) \propto x(t)$. In practice, however, it is impossible to provide an ultrasonic source having infinite bandwidth due to physical limitations. As a compromise it has been found that a finite wide-band ultrasonic source may perform well, provided that the modulated wave is transmitted by an ultrasonic transducer 11 with a wide bandwidth. It is thus one objective in the present invention to develop such an ultrasonic transducer.

Some publications describing parametric speakers, also known as "parametric arrays" or "parametric audio systems", include K. Aoki, T. Kamakura and Y. Kumamoto, "Parametric Loudspeaker – characteristics of acoustic field and suitable modulation of carrier ultrasonic", Electronics and Communications in Japan, Part 3, vol 74, No. 9, 1991; D. T. Blackstock, "Audio application of the parametric array", J. Acoust. Soc. Am., 102, 3106(A), 1997; and M. Yoneyama, J. Fujimoto, Y. Kawamo, and S. Sasabe, "The audio spotlight: an application of non-linear interaction of sound waves to a new type of loudspeaker design", J. Acoust. Soc. Am., 73(5), 1983. In these conventional parametric audio systems, the parametric speaker/ultrasonic transducer typically includes a large amount of ceramic-based piezoelectric bimorph elements. One drawback of such a parametric speaker is its narrow bandwidth, which results in audible sound distortion. Another drawback is that its manufacturability and repeatability are not good, which results in it being impractical for production.

Parametric speakers using a monolithic thin film provide a practical and cost-effective way to reproduce directional sound. Such speakers are described in

US 6, 044,160 issued to E.G. Norris, and US patent application 2001/0007591 A1 by F. J. Pompei. These are basically electrostatic ultrasonic transducers/emitters. The basic structure of this type of emitter is that an insulating thin film is provided on a flat metallic back-plate having shallow grooves, and a thin metallic layer is deposited/sputtered onto the thin film. A DC voltage bias is applied across the insulating thin film between the metallic layer and the back-plate, thereby causing extensive pre-stress in the film resulting in a curvature of the monolithic film. An AC excitation is superimposed onto the voltage across the insulating film to induce high-frequency vibrations of the thin film. Both the resonant frequency and the electro-acoustic transfer efficiency are strongly dependent on the groove depth and the thin film's geometry, so the electrostatic parametric speaker requires both an accurate back-plate structure and a very thin film (of the order of a few microns). These pose some difficulties to the fabrication and mass production of this type of speaker/transducer.

By contrast, piezoelectric film ultrasonic emitters provide a cost-effective alternative for use in a parametric audio system. Such a device is described in US patent no. 6,011,855, issued to A. R. Selfridge and P. Khuri-Yakub. This is a piezopolymer-based parametric speaker in which a thin piezoelectric film is disposed across an emitter plate having many through holes. A pressure source, such as one provided by a vacuum pump, is coupled to the a back-cavity of the emitter plate, and develops a bias pressure at the apertures to cause extensive pre-stress in the film, and deform the film into an arcuate configuration capable of constricting and extending in response to variations in an applied electrical input. However, the application of a constant pressure differential to such a structure to maintain the required curvature of the piezoelectric film is not a trivial task. In addition, as US 6, 011,855 describes in relation to its Fig. 5, the emitter has a bandwidth around 37KHz of only 5 kHz, which is not wide enough to cover the human audio frequency range

(which is about 20 Hz to 20 kHz), and thus if such an emitter is used to reproduce sound there will be an audible distortion at high audio frequencies. It is possible to increase the bandwidth of the emitter by increasing the carrier frequency (for example, the -6dB bandwidth reaches 16kHz when the carrier
 5 frequency is 93kHz), but raising the carrier frequency results in a quick attenuation of the ultrasonic sound, so that the ultrasound beam will have a shorter length.

In order to reduce sound distortion due to the narrow bandwidth, some efforts
 10 have been made to develop equalisation or pre-processing methods in the parametric audio system. Examples include T. D. Kite, J. T. Post and M. F. Hamilton, "Parametric array in air: distortion reduction by preprocessing", J. Acoust. Soc. Am., 103 (1998), but these approaches can only reduce distortion within limits. They cannot eliminate it completely.

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Apart from US 6, 011,885, discussed above, another publication in which phased-matched air ultrasonic transducers are described which use a corrugated PVDF film is the article "Phased-matched air ultrasonic transducers using corrugated PVDF film with half wavelength depth", M.
 20 Toda, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control, Vol. 48, No. 6, 2001. In this paper, the author mentions in the introduction section the concept of highly directional speakers in the audio range using amplitude-modulated, high power, non-linear ultrasonic wave propagation, but the majority of the text is directed to a transducer which is
 25 not said to be suitable for use in a parametric speaker. Note that it is more desirable for such a speaker to have both the narrow beam pattern almost without side-lobes and the wide bandwidth. The transducer includes a piezoelectric film sheet which is held in a sinusoid-like corrugated configuration by sinusoid-like support members extending along the edges of
 30 the sheet. Due to the sinusoid-like configuration of the sheet, a depth of half a

wavelength is required to ensure that the corrugated PVDF ultrasonic transducer has phase-matching and good directivity. However, it is not a trivial task to maintain this requirement since there often is a significant tolerance between theoretical calculations and actual fabrication. In this paper, a trial and error approach is adopted to vary some parameters to achieve a good performance, but this will result in low yield of ultrasonic transducers with inconsistent characteristics.

Summary of the Invention

10 The present invention aims to provide a new and useful parametric speaker. Preferably, the speaker at least mitigates the disadvantages of the known speakers described above.

As discussed below, preferred embodiments of the present invention are speakers which are lightweight, thin and compact. Advantageously, these
15 speakers may be resonance tuned and have selectable beam directivity. Also advantageously, the speaker has a wide bandwidth to reduce demodulated sound distortion, and a narrow beam pattern to reproduce a highly-directional audible sound.

In general terms, the present invention proposes in a first aspect that a
20 speaker includes a flexible piezoelectric film having electrodes for applying a voltage signal to the film. The film is fixed to a substrate and is maintained in corrugations.

In a first form of this concept the film is fixed to the substrate at fixing positions which are at at least two different positions in the thickness direction of the
25 substrate. The fixing portions hold the film in a corrugated configuration including generally concave corrugations parallel to the fixing portions, the

corrugations being supported at their sides and also at a central region by respective ones of the fixing portions.

The substrate may furthermore include a surface formation for giving the corrugations a desired curvature over a portion of the area of the piezoelectric film (thereby controlling the curvature of the remainder of the corrugations).
 5 For example, the substrate may include partially-cylindrical concave shallow notches.

The shapes of the corrugations are well-defined, thus producing a high sound quality.

10 Typically, the substrate includes elongate ridges (typically straight), and the adhesive membrane adheres the piezoelectric film to the substrate at fixing portions which comprise the ridges. Typically, the ridges give the substrate a surface which includes grooves which are rectangular (or square) in cross-section. The volume between the piezoelectric film and the substrate
 15 constitutes a back-cavity.

The piezoelectric film may optionally be adhered to the substrate using an adhesive film extending between the film and the substrate. The adhesive membrane may take the form of a double-sided tape (i.e. a tape having adhesive on both surfaces) having uniform thickness. This tape may provide a
 20 high holding strength and durability.

Both the bonding tape and the reduced back-cavity in the substrate provide a measure of damping to the motions of the piezoelectric film, and thus broaden the frequency response of transducer.

We have determined that a transducer in accordance with the invention may
 25 achieve a high carrier frequency (preferably, in between 55~70kHz), a wide bandwidth (preferably, a -6dB bandwidth over a range of 10kHz), and a narrow beam pattern (preferably, a -6dB beamwidth of less than 8°). These

features make it possible to provide an alternative to conventional transducers: a transducer which projects highly-directional sound with reduced distortion when a simple signal pre-processing algorithm (such as square rooting) is adopted for an input audio signal.

- 5 In a further aspect the invention provides a speaker as described above in combination with a power amplifier.

In a further independent aspect of the present invention, which is combinable with the first aspect of the invention, the power amplifier used to drive the ultrasonic transducer utilizes an electrical resonance frequency which
 10 matches the mechanical resonance frequency. This enhances enhance system efficiency. A capacitance and/or inductance may be provided to produce the resonance. A resistor (such as a variable resistor) may be present to broaden the frequency response in the drive circuit by providing damping. Preferably, the resistor is variable.

- 15 The invention further provides a sound generation system including a signal processing unit which receives an input signal including an audio signal, modulates an ultrasonic signal using the input signal, and outputs a modulated ultrasonic signal which is input to a combination of a speaker and/or a power amplifier as defined above.
- 20 Additionally, the invention proposes a method of generating sound by applying electric signals to the speaker unit proposed by the invention and/or using the power amplifier proposed by the invention.

Brief Description of The Figures

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

Fig. 1(a) shows schematically a known parametric speaker system;

FIG. 1(b) shows schematically a block diagram of a known signal pre-processing scheme for use in the system of Fig. 1(a);

Fig. 2, which is composed of Figs. 2(a) to 2(d), illustrates a speaker which is a first embodiment of the invention;

5 FIG. 3 shows a curved PVDF membrane element in the first embodiment of the invention;

FIG. 4 illustrates the operating mode of the PVDF film of the embodiment of Fig. 2; and

10 FIG. 5 shows schematically a power amplifier for use with an ultrasonic transducer according to the invention.

Detailed Description of the embodiments

Referring to FIG. 2, a substrate 20 for forming an ultrasonic transducer is depicted which is an embodiment of the invention. This transducer may be
15 used, for example, in the system of Fig. 1(a) or 1(b).

Fig. 2(a) shows the substrate 20 in a view looking directly towards its surface. Fig. 2(b) is a perspective view. Fig. 2(c) is a view of a cross-section of the
20 substrate 20 in the plane shown as A-A in Fig. 2(a). Fig. 2(d) is an enlarged view of the portion of Fig. 2(c) indicated by the circle B.

The substrate 20 can be used to produce a transducer by adhering to it a laminar film (not shown) of flexible and monolithic piezo-polymer (such as PVDF). The substrate 20 has a surface (the upper surface in Fig. 2(b))
25 directed towards the film and including longitudinally-uniform grooves 22 divided by ridges 21a, 21b. The surface of the substrate 20 further includes partially-cylindrical concave shallow notches 27a, 27b, 28a, 28b, 28c. Some of these notches 27a, 27c are provided in rows at the two respective ends of the substrate. Other of the notches 28a, 28b, 28c are relatively narrower (i.e.

in the direction along the grooves 22) and are provided in rows. The rows of notches 28a, 28b, 28c are substantially normal to the ridges 21a, 21b.

The piezo-polymer is bonded onto the substrate 20 by an adhesive, such as
 5 an adhesive membrane (not shown). Specifically, the piezo-polymer is partially bonded onto the tops of the ridges 21a, 21b of grooves 22 and to the surface of notches 27a, 27b, 28a, 28b, 28c. The remaining part of the piezo-polymer is free, and maintained in corrugations parallel to the fixing portions 21a, 21b, each of which is concave on the surface facing away from the
 10 substrate (the upper surface in Fig. 2(b)) and covers a respective longitudinally-extending back-cavity.

For clarity, the transducer of Fig. 2 includes only five pairs of grooves 22. However, the invention is not limited to this. Actually, in other embodiments of
 15 the invention it is preferred for the transducer to include many rows. Furthermore, a single transducer may be formed having many elements such as that shown in Fig. 2 to provide a large total area, with many columns or rows. The provision of a large area including many columns or rows is desirable since this may increase the sound pressure level (SPL), improve the
 20 directivity of the sound-beam and avoid any saturation of the medium at high intensities.

Fig. 3 illustrates the vibration of a partially-cylindrical element 31 of PVDF (i.e. one of the corrugations) held at its edges. It can be shown that the dominant
 25 frequency of a cylindrical PVDF sound emitter is given by:

$$f_c = (1/2\pi r)\sqrt{Y/\rho} \quad (1)$$

where Y is the average Young's modulus of the PVDF with electrodes, ρ is its average density, and r is the radius of curvature. For a partially-cylindrical PVDF sound emitter, it has been experimentally verified that the dominant

frequency is related to the curvature as well as other factors like the constraint and arc angle. According to equation 1, the central frequency of the ultrasonic transducer of Fig. 2 is mainly determined by its curvature radius once the piezopolymer membrane is chosen. The substrate 20, as shown in Fig. 3, provides an effective way of maintaining a partially-cylindrical shape, using the constraints of three points A, B, C. Without these three points it is much harder to ensure that the actual resonant frequency is close to its design value, since the piezoelectric membrane tends to be an irregular arc or other shape due to its higher flexibility. Thus, by means of the concept of supports at differing heights above the main substrate body, a resonance-tuned sound projector should be achievable.

Note that the central frequency of ultrasonic transducer in embodiments of the present invention is typically between 40~80kHz. It has been experimentally verified that having a lower central frequency tends to cause the lowest harmonic component in the modulated ultrasonic carrier signal to fall into an audible range when the square root pre-processing is adopted. In addition, a lower central frequency also tends to weaken the directivity of sound beam. However, it is not always desirable to increase the central frequency since too high a central/carrier frequency will result in a quick attenuation of ultrasonic sound. It is thus preferable in the present invention that the central frequency of ultrasonic transducer is between 45~75kHz. Particularly for a far-field application, the resonant frequency is preferably between 45 and 55kHz. Particularly for a near-field application, the resonant frequency is preferably between 60 and 75kHz.

It is preferable in the present invention that the central frequency or carrier frequency of ultrasonic transducer is its 1st structural resonance frequency, and the vibration mode at this frequency is a so-called breath-mode, since all of these will enhance the fluid-solid coupling as well as the SPL of the

- ultrasonic transducer. The vibration mode at the 1st natural frequency tends to be a breath-mode as the α is decreased. However, it is not a trivial task to maintain a PVDF membrane to have a “shallow” and partially-cylindrical shape with a reduced α due to its elastic recovery. In the embodiment of Fig. 2, the central point of each partially cylindrical portion of the PVDF membrane is bonded onto a respective one of the short ridges 21b. In this configuration the partially cylindrical portions are each divided into two (subtending an angle of only $\alpha/2$), resulting in a breath-mode at the first natural frequency.
- 10 We have experimentally verified that the sound beam's directivity is related to the width w of the ridges 21a, 21b. In this regard, the main lobe starts to become narrower when w increases. However, with increasing w , deleterious side lobes are generated. Preferably, the value of w is less than 1.0 mm.
- 15 The height of back-cavity 31 is preferably less than one wavelength so as to eliminate any possible backside wave reflection. The trapped air in the cavity may function as a squeeze damper to suppress the mechanical resonance of the piezo-polymer 31 and broaden the bandwidth of the ultrasonic transducer.
- 20 However, a negative effect of the trapped air is that it may shift the resonant frequency from its design value. One way of addressing this problem (in cases where it is significant) is to provide holes to release air extending from the back cavity 32, e.g. through the entire thickness of the substrate 20.
- 25 The piezo-electric film is adhered to the substrate. This may be by an adhesive membrane which lies directly on the substrate 20 over substantially the whole area of the adhesive membrane. It may be formed by using either tape or epoxy. Preferably, a tape is adopted since it may achieve the uniform thickness. One particularly preferred possibility is for the adhesion material to be 3MTMVHBTM double-sided tape which has a high holding strength and
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durability. In addition, it may dampen the mechanical vibration, resulting in the extension of the bandwidth of ultrasonic transducer.

A substrate 20 may be formed from metal such as aluminium, copper or
 5 brass, or from a plastics material such as ABS. Aluminium alloy such 6061Al is a preferable alternative since it may be fabricated into a rigid structure with low density, resulting in a lightweight and panel-like highly-directional sound projector. In addition, aluminium has low acoustic impedance, which may be matched with the piezo-polymer 31.

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Conventional CNC machining may be adopted in fabrication of the substrate 20. Alternatively, the substrate 20 may be formed by moulding, which may prove cost-effective in mass production.

15 It is preferable that the piezo-polymer 31 is poly-vinylidene fluoride (PVDF) since PVDF has a vast dynamic range, low acoustic impedance, high elastic compliance, high dielectric strength and low cost. Moreover, it may be fabricated into unusual designs. The piezo-polymer 31 is provided with electrodes for applying a voltage to it. The material for electrodes may be
 20 silver ink.

The PVDF membrane is preferably formed such that each of the corrugations 31, clamped at its two sides, vibrates in the d_{31} mode, and thereby produce a sound wave propagating normal to the film's surface. The PVDF d_{31} mode is
 25 illustrated in Fig. 4.

In order to obtain a high sound pressure level, it is required to provide a significant driving voltage to the PVDF films of the embodiments of the
 30 transducer described above. Maximum system efficiency may be achieved

when the drive electrical resonance frequency matches the mechanical resonance frequency of the ultrasonic transducer. Fig. 5 shows a basic schematic of a power amplifier for the ultrasonic transducer in the present invention. The modulated signal $y_i(t)$ is amplified to an appropriate level by
5 an operational amplifier 81, which may alternatively be a combination of a series of linear power amplifiers. The output of amplifier 81 is applied to a step-up transformer 82 to increase the driving voltage further. Here the equivalent circuit of the PVDF transducer is denoted as a capacitance 85. A transformer 82 and a series inductor 83 are provided to make it possible to
10 obtain an electrical resonance. Since the PVDF emitter in the present invention is a wide-band transducer, a variable resistor 86 and a variable capacitor 84 are introduced to dampen and broaden the frequency response of the drive circuit so as to match the dynamic characteristics of the transducer. Such a power amplifier may maximise the transfer efficiency from
15 electrical energy into mechanical energy.

Although only a few embodiments of the invention have been described above, many variants are possible within the scope of the invention as will be clear to a skilled reader. In particular, the speaker may be made of large size,
20 so as to create a high output sound pressure level, and achieve a narrow beam pattern. Additionally, the parameters of the speaker may be optimised to increase the conversion efficiency from ultrasonic energy to audible sound.

Claims

1. A speaker unit for a sound generation system, the speaker unit comprising:
 - a flexible piezoelectric film having electrodes for applying a voltage
5 signal to the film; and
 - a substrate having a surface facing towards the piezoelectric film;
 - the piezoelectric film being attached to the surface of substrate at elongate fixing portions, the fixing portions maintaining the piezoelectric film in a configuration including concave portions which are elongate and parallel to
10 the fixing portions, the fixing portions including first fixing portions at either edge of the elongate concave portions of the piezoelectric film, and at least one second fixing portion at a central region of each elongate concave portion of the piezoelectric film.
2. A speaker unit according to claim 1 in which the substrate includes
15 elongate first ridges projecting from its surface which faces towards the piezoelectric film, the first fixing portions being the tops of the first ridges.
3. A speaker unit according to claim 2 in which said second fixing portions are provided on second ridges projecting from the same surface of the substrate and shorter than the first ridges.
- 20 4. A speaker unit according to claim 2 or 3 in which the ridges give the substrate a surface profile which includes grooves.
5. A speaker unit according to claim 4 in which the grooves are rectangular or square in cross-section.

6. A speaker unit according to any preceding claim in which the substrate includes for each corrugation one or more air holes communicating with a back space between the corrugation and the substrate.
- 5 7. A sound generation system including an oscillator for generating an oscillating signal, a modulating unit for modulating the ultrasonic signal according to an audio-frequency signal, a power amplifier for amplifying the modulated signal, and a speaker unit according to any preceding claim arranged to receive the output of the power amplifier as a voltage across the
10 electrodes.
8. A sound generation system according to claim 7 in which the power amplifier includes a resistor and also a capacitor and/or an inductor for generating a resonance.
9. A sound generation system including an oscillator for generating an
15 oscillating signal, a modulating unit for modulating the ultrasonic signal according to an audio-frequency signal, a power amplifier for amplifying the modulated signal, and a speaker unit arranged to receive the output of the power amplifier as a voltage across the electrodes, the power amplifier including a resistor and also a capacitor and/or an inductor for generating a
20 resonance.
10. A sound generation system according to claim 8 or 9 in which the resistor is a variable resistor.