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A Parametric Speaker and a method of making it

Field of the invention

The present invention relates to a parametric speaker, and to a method for producing a parametric speaker.

5 Background of Invention

A major concern when designing a loudspeaker is to enable it to produce pure sound. One common solution to this is to use a combinations of woofer, mid-range and tweeter speakers to achieve a high-fidelity effect.

- 10 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. An audio signal 1 input from the left of the figures 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
- 15 oscillator 7 which produces vibrations at a single frequency in the ultrasonic range. The result is transmitted to a power amplifier 9, and from there to a parametric speaker 11. Let us assume that the speaker 9 emits two ultrasonic waves with frequencies f_1 and f_2 . The ultrasonic waves have a non-linear interaction with the air, to generate sound waves having tones f_1+f_2 and f_1-f_2 .
- 20 Of these, the difference signal f_1-f_2 is usually more interesting since it may be in the audio range. The system is designed such that this difference frequency corresponds to the frequency of the audio signal 1 input to the left of Fig. 1. 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
- 25 audio frequency ranges. More generally, if the audio signal 1 contains multiple audio frequency components of differing amplitudes, then the preprocessor unit 3 aims to operate such that these amplitudes are equal to the corresponding amplitudes of the audio frequency signals produced by the



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ultrasonic wave. Thus, a parametric speaker provides an alternative way of providing audible sound radiation.

An advantage of using a parametric speaker compared to a conventional speaker is that it is relatively easy to produce a directed beam of ultrasonic waves, compared to audio waves, so parametric speakers make it possible to produce highly directional audio sound, which is interesting for many applications. 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 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
 5 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.
 15 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
 20 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
 25 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
 30 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

- 5 The present invention aims to provide a new and useful parametric speaker, and a method of making the new 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
10 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 that a speaker includes a
15 flexible piezoelectric film having electrodes for applying a voltage signal to the film. The film is fixed to a substrate which holds the film in a corrugated configuration, in which the substrate is firmly attached to the film between the corrugations and the film is free to move at the corrugations.

The film may be firmly attached to the film between the corrugations using an
20 adhesive, or alternatively by clamping it between the substrate and a cover. In the latter case, the cover preferably includes apertures for permitting sound generated by the film to be transmitted.

The substrate may include support elements for supporting the corrugations of the film, but not firmly fixed to the film. The elements may be arranged in
25 columns which correspond to the respective corrugations. Optionally, the support elements may be sections of cylinders, parallel to the axis of the cylinders.

Optionally, the support elements may be convex elements. If so, then in the case that a cover is provided, the cover may include concave depressions corresponding in position to the convex elements and deeper than the height of the convex elements, so that the film is not firmly clamped between the support elements and the cover.

Additionally, the invention proposes a method of forming a speaker which, in general terms, is to attach a piezoelectric film to a substrate such that the film is corrugated and the portions of the film between the corrugations are firmly fixed to the substrate whereas the corrugations themselves are not so fixed.

Additionally, the invention proposes a method of generating sound by applying electric signals to the speaker proposed by the invention.

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:

Fig. 1 shows schematically a known parametric speaker system;

Fig. 2 is an exploded view of a parametric speaker which is a first embodiment of the invention;

Fig. 3 is composed of Fig. 3(a) which is an exploded cross-sectional view of the embodiment of Fig. 2, Fig. 3(b) which is a cross-sectional view of the assembled speaker, and Fig. 3(c) which is an enlarged view of part of Fig. 3(b);

Fig. 4 is composed of Fig. 4(a) which illustrates the operating mode of the PVDF element of the embodiment of Fig. 2, and Fig. 4(b) which illustrates the working principle of the embodiment of Fig. 2;

Fig. 5, which is composed of Fig. 5(a) and 5(b), is perspective views of respective bimorph PVDF films which are suitable for use as an element of the embodiment of Fig. 2;

Fig. 6 is composed of Fig. 6(a) and Fig. 6(b) which respectively show two more PVDF films which are suitable for use as an element of the embodiment of Fig. 2;

Fig. 7 is a top view of an alternative form of the solid support of the
5 embodiment of Fig. 2;

Fig. 8 shows experimental measurements of the sound pressure level vs. frequency of the embodiment;

Fig. 9 is composed of Fig. 9(a) and 9(b) which respectively show experimental measurements of sound pressure level vs. angle of the second
10 embodiment for (a) horizontal beam directivity and (b) vertical beam directivity, respectively;

Fig. 10, which is composed of Figs. 10(a) to 10(l), shows a second embodiment of the present invention;

Fig. 11 is an exploded view of a third embodiment of the invention;

Fig. 12 is a simplified, cross-sectional view of the third embodiment of
15 the invention; and

Fig. 13, which is composed of Figs. 13(a) to 13(c), shows a substrate element for use in a fourth embodiment of the present invention.

20 Detailed Description of the embodiments

Referring to Fig. 2, the parametric speaker which is the first embodiment of the present invention is shown in an exploded view. The speaker includes three main elements: a substrate element 10, a flexible piezoelectric film 20
25 and a cover element 30.

The substrate 10 is generally rectangular and laminar. It has a substantially flat surface 12 which is perpendicular to a direction labelled the z-direction in Fig. 2. The surface 12 carries a number of discrete, partially-cylindrical convex support elements of two kinds. A first kind of support elements are convex

partially-cylindrical protrusions 11 at two opposite sides of the substrate 10. The second kind of support elements 13 are narrower. Each of the support elements 11, 13 may be treated as a portion of a notional respective cylinder, and the cylinder for each of the first support elements 13 is coaxial with the cylinders of two of the protrusions 13. The cylinders for all the support elements 11, 13 have axes extending in a direction in the plane of the surface 12 called the x-direction. Specifically, the first support elements 13 are in an array having columns (parallel to the x-direction) and rows (parallel to an direction labelled the y-direction and orthogonal to both the x- and the z- directions). The columns of second support elements 13 are aligned with two of the first support elements 11, and all the support elements 11, 13 extend to the same height above the plane of the surface 12. In this embodiment, the array of the second support elements 13 has six columns and nine rows, but the invention is not limited to this number of columns and rows. In fact, in a large speaker a correspondingly larger number of columns and rows is desirable to increase the sound pressure and avoid any saturation of the air medium at high sound levels.

The piezoelectric film 20 is preferably a piezo-polymer which in use overlies the substrate 10. It carries two flexible electrode layers (not shown) substantially covering its respective sides. The electrodes may be made by a conventional method, for example using silver ink. The piezo-polymer may be polyvinylidene fluoride (PVDF) or one of its co-polymers. This material has a very high dynamic range, a low acoustic impedance, a high elastic compliance, a high dielectric strength and low cost. Moreover it can be fabricated in complex designs (a feature which is particularly advantageous for the other embodiments described below).

The cover 30 includes apertures 33 which are slots elongate in the x-direction. The apertures 33 are aligned in the y-direction with columns of the second support elements 13, and in the x-direction with spaces between the support

elements 11, 13 along the corresponding column. The cover 30 further includes concave depressions 31 in its lower surface positioned in the y-direction in locations corresponding to the columns of support elements 11 and extending in the x-direction along the whole length of the cover 30 (except when they intersect with the apertures 33).

A cross section of the substrate 10, film 20 and cover 30 is shown in Fig. 3(a) exploded, and in Fig. 3(b) joined to form the speaker unit. When they are joined together, the substrate 10 and the cover 30 co-operate to shape the piezoelectric film 20 into a configuration such that it has corrugations 14 with an axis parallel to the x-direction and spaced apart by flat portions 16 of the film parallel to the surface 12. In the flat portions 16 of the film 20 the film is firmly fixed (by clamping between the substrate 10 and the cover 20) to the substrate 10, so these portions of the substrate are referred to as fixing portions 18 of the substrate 10. The natural lengths of the parts of the film 20 between the fixing positions 18 of the substrate 10 is greater than the spacing of the fixing positions 18, so that the substrate holds the film 20 in a corrugated configuration. The support elements 11, 13 ensure that the corrugations flex away from the surface and correspond to the respective columns of support elements 11, 13. Due to the corrugations 14, the film 20 behaves as a sound radiation device, which as described below may be tuned in both resonance and beam-directivity. The piezoelectric film 20 is clamped onto the substrate 10 at the fixing positions 18 where the substrate is flat, and other parts of the film 20 are not clamped.

In contrast to the proposal for a transducer made by M. Toda in the article referenced above, the corrugations of the embodiment of Fig. 2 do not have a sinusoid-like shape, which means that there is no limitation that the height of the corrugations should be half of the wavelength of the emitted sound. By contrast, in the embodiment of Fig. 2 the corrugations have a shape which is

substantially a portion of a cylinder. In further embodiments discussed below, the corrugations take other shapes.

During the assembly of the speaker shown in Fig. 2, the cover 30 is pushed onto the substrate 10 slowly, so that the film 20 is naturally flexed to follow the profile of the substrate 10 and cover 30, and no excessive internal pre-stress is induced in the film 20 during this procedure. At the fixing positions 18 the cover 30 is pressed against the substrate 10 with a force F , which is suitably chosen and controlled. As has been noted above, a pre-stress in the film 20 has an effect on the film's elastic stability, the speaker's central frequency and its bandwidth. The cover 30 may be fixed to the substrate 10 by screws (not shown) or any other type of fixture.

Note that the film 20 is clamped or bonded onto the substrate 10 only at the part where the substrate 10 is planar. Along the entire length of the columns including the support elements 11, 13 the film 20 is not clamped or bonded, but only in contact with the substrate at the support elements 11, 13. There is a tolerant match of the substrate's support elements 11, 13 and the cover's concave depressions 31, as illustrated in Fig. 3(c) which shows an enlarged view of part of the structure of Fig. 3(b) (omitting hashing for simplicity). The height d of the convex elements 11, 13 above the surface 12 is less than the depth D of the concave depressions 31.

One of the functions of the support elements 11, 13 is to maintain the corrugated shape of the film 20 without extensive internal pre-stress in the film 20. Another function of the support elements 11, 13 is to provide mechanical damping. Friction between the film 20 and the support elements 11, 13 transfers mechanical energy into heat energy which is dissipated. In this way, the mechanical resonance of the speaker is suppressed, which results in a speaker having a wider bandwidth.

Note that there is a space 19 between the film 20 and the substrate 10 in the parts of the columns other than the support elements 11, 13. The height of this space is preferably less than one wavelength so as to eliminate any possible backside wave reflection. However, it should preferably be more than
 5 0.5mm so as to eliminate any possible air squeeze-film damping. Optionally, and in particular for speakers such that the space 19 between the film 20 and the substrate 10 is high, a sound absorption material such as foam may be inserted into the space 19, so as to reduce any possible backside wave reflection. The spacing of the support elements 11, 13 along any given row
 10 does not follow a strict requirement, but presently a spacing in the range 10mm to 30mm, for example about 20mm, is preferred.

The substrate 10 and cover 30 may be formed of materials which are either a metal such as aluminium, copper or brass, or a plastics material such as ABS (Acrylonitrile Butadiene Styrene). In the case that it is metal, aluminium is the
 15 presently preferred alternative since it has low density and low acoustic impedance, but in this case ultra-precision machining such as CNC (Computer Numeric Control) should be adopted to ensure that the coupling between the substrate 10 and the cover 30 is substantially perfect. Alternatively, one of both of the substrate 10 and cover 30 may be a plastics
 20 material, and moulded to have the desired shape. This latter possibility is cost-effective when the speaker is to be mass produced. Preferably, both the substrate 10 and cover 30 are thin and lightweight, which results in a compact and portable speaker unit.

Turning to Figs. 4(a) and 4(b), which show the film 20 schematically with a
 25 voltage supply connected to its electrodes, the mode of oscillation of the film 20 is shown. The film 20 is preferably operated in its d_{31} mode, illustrated in Fig. 4(a) in the case that the film 20 is flat. If the film 20 were flat, no significant sound wave would be produced. However, since in the embodiment the film 20 is supported in corrugations by the support elements

11, 13 and the fixing positions 18, its vibrations in the d_{31} mode will produce sound waves parallel to the film's surface. An accurately controllable partially cylindrical PVDF sound emitter, such as the parts of the PVDF overlying the second support elements 13, has a central frequency given by:

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

Where Y is the averaged Young's modulus of the film 20 with its electrodes, ρ is its average density, and r is the radius of curvature. Once the PVDF material is chosen, equation (1) allows us to choose the central frequency of the speaker by selecting its radius of curvature. Thus, a resonance-tuned parametric speaker is achievable. Note that the central frequency for the parametric speaker of the present embodiments is more than 40kHz, more preferably over 50 kHz, so as to reduce or even eliminate the risk that the lowest frequency component in the modulated ultrasonic carrier signal falls into the audible range.

The larger the effective area of the film 20 the higher the sound pressure level generated by the speaker, and thus the higher the intensity of the sound. Thus, a speaker with a large enough film 20, or a plurality of films 20 (each being a separate speaker element), is able to achieve a parametric speaker which is thin, flat, compact and cost-effective.

In an alternative form of the first embodiment, the film 20 can be replaced by a bimorph PVDF film 120 as shown in Fig. 5(a), made up of two PVDF films 121, 122. Such a film gives the speaker a higher actuation capability and a higher electro-acoustic transfer efficiency.

In another alternative form of the first embodiment, the film 20 can be replaced by a bimorph PVDF film 220 shown in Fig. 5(b) made up of two PVDF films 221, 222 spaced apart by a layer of a visco-elastic damping material 223. The function of the visco-elastic material is to suppress the

mechanical resonance of the PVDF films and increase the bandwidth of the speaker.

In a further alternative form of the first embodiment, shown in Fig. 6(a), the film 20 is replaced by a PDVF film 320 having a pattern of elongate electrodes 321. These electrodes are given a pattern which permits beam steering (i.e. directing the beam of ultrasonic waves produced by the speaker). Each patterned part 321 is equal to one speaker element. By means of time-delayed driving of each speaker element 321, the sound beam direction may be controlled to sweep one dimensionally by powering the electrodes 321 in a linear sequence. Alternatively, the film may be of the form 420 shown in Fig. 6(b), having a two-dimensional pattern of electrodes 421, and in this case the sound beam direction may be controlled to vary in a two-dimensional pattern.

A further variant of the second embodiment is for the substrate 10 to be replaced by the substrate 110 shown in top view in Fig. 7(a), in which the convex second support elements 113 are in a different array from the second support elements 13 of the substrate 10. Again, the x-direction is the direction in which the corrugations extend. Fig. 7(b) shows a cross section of a part of the substrate 110 indicated as B-B in Fig. 7(a). This part of the substrate includes a single second support element 113, and Fig. 7(b) indicates the angle α subtended by the second support element 113, and the radius of curvature r of the second support element 113.

In many applications, it is preferable that the speaker of the present invention should produce a narrow and dense sound beam with little or no side lobes. It can be verified that the beam pattern is related to the carrier frequency and the geometrical parameters of the array: the spacing g of the convex elements 113 in the y direction, the spacing d of the convex elements 113 in the x direction, and the value of α .

In an exemplary case, the parameters are $r=4\text{mm}$, $g=1\text{mm}$, $d=20\text{mm}$ and $\alpha=60^\circ$, and the thickness of the piezoelectric film is 28 micrometers. With these parameters, we have determined experimentally that the relationship between the sound pressure level and frequency is as shown in Fig. 8.

5 Figs. 9(a) and 9(b) show the variation of the sound pressure level vs. angle for the horizontal plane (i.e. parallel to the xz-plane) and the vertical plane (i.e. parallel to the yz-plane). Thus, the peak of Figs. 9(a) and 9(b) is indicative of the beam directivity. As can be seen from these figures, the directivity is high, despite the absence of any focusing, and there are almost no side lobes. The
10 bandwidth is high: the -6dB bandwidth is far more than 10kHz , as may be seen from Fig. 8.

Figs. 10(a) – 10(f) show the construction of steps of a second embodiment of the invention. In this embodiment, the substrate 210 is initially used together with a shaping member 211, as a combination 219. The members 210, 211
15 are shown separated in Fig. 10(a) and in combination in Fig. 10(b). The shaping member 211 is a thin plate 212 having shaping elements 213 formed on it; the shaping elements 213 are discrete (i.e. spaced from each other), stand up from the plate 212 in a regular array, and have straight sides and a rounded top surface. The substrate 210 is a plate 215 having a pattern of
20 openings 217 for receiving the respective shaping elements 211. The openings 217 are defined between rims 218 which extend orthogonally in the plane of the plate 215. The rims extending in the x-direction have substantially flat tops and constitute the fixing portions of the substrate 210, but the rims extending in the y-direction have convex upper surfaces and constitute
25 support elements.

A thin layer of adhesive 250 may be provided on the tops of the rims 218 as shallow trenches, as shown in Fig. 10(c) which is a cross-sectional view of part of the combination 219 shown in Fig. 10(b) along the line C-C. The

adhesive's volume and thickness should be controlled, especially to ensure that it is thin.

As shown in Fig. 10(d), a speaker is formed by slowly bringing the combination 219 towards the cover 230 with the film 20 (which may be
5 replaced by any of the films 120, 220, 320 or 420) sandwiched between them, as shown in Fig. 10(e). The cover contains concave depressions 231 corresponding to the shapes of the support elements 213 (and thus to the corrugations which are to be formed in the film 20), but need not contain apertures. The combination 219 and cover 230 should be brought together
10 with a force and a velocity such that excessive internal pre-stresses in the film 20 are avoided. Due to the adhesive 250 on the tops of the rims 218, the film 20 will be bonded to the fixing portions of the substrate 210. Then, when the bond is secure, the cover 230 can then be removed.

Similarly, the shaping member 211 is also be removed, so that the film 20 is
15 left supported by the element 210 alone, as shown in Fig. 10(f). A space exists beneath the lower surface of the corrugations in the film 20 (as viewed in the orientation of Fig. 10(f)). This space increases the sound pressure level of the speaker. An exploded view of the speaker is given in Fig. 10(g).

In order to cause the speaker to emit ultrasound only in a single direction, a
20 tray-like member 260 having side walls 261, as shown in Fig. 10(h), is provided, and attached to the bottom of the element 210, to form the completed speaker shown in Fig. 10(i). The speaker shown in Fig. 10(i) is thin, lightweight, and compact.

A chamber is defined between the element 210 and the tray-like member 260.
25 Particularly, in the case that the maximum height in the chamber is more than one wavelength, sound absorption materials such as foam elements 270 may be placed onto to the plate 260, so that they are enclosed in the chamber. These elements reduce any possible sound reflection.

Fig. 11 shows a further embodiment of the invention. In this case, both the substrate 310 and the cover 330 are formed with narrow ridges 311, 331 on their opposing faces. Each ridge is preferably formed with a chamfer or fillet (not shown) on its top surface. The cover 330 further includes rectangular apertures 333. When the substrate 310 and cover 330 are placed together sandwiching a film 20 (or alternatively any of the films 120, 220, 320 or 420), and with the ridges 311 interleaved with the ridges 331, corrugations are formed in the film 20 parallel to the ridges 311, 331, which is the x-direction in Fig. 11.

10 The substrate 310 may include an adhesive on the surface 312 between the ridges 311, such that the film 20 becomes adhered to the substrate 310 at the locations where the ridges 331 on the cover 330 force the film 20 into contact with fixing portions of the surface 312. In this case, the cover 330 may optionally be removed, to form the completed speaker (note that in this case, 15 it is unnecessary for the cover 330 to include the apertures 333). The completed speaker is shown in cross-section in Fig. 12. Note that the film 20 is not secured to the convex rounded tops of the ridges 311. The ridges 311 play the role of support elements.

In all the of the first three embodiments the substrates 10, 110, 210 and 310 20 include convex support elements. However, the invention is not limited in this respect. For example, Figs. 13(a), 13(b) and 13(c), show different views of a substrate 410 for forming a fourth embodiment of the invention. The substrate 410 has a generally rectangular form, composed of first elongate members 411 extending in the x direction and second elongate members 412 extending 25 in the y-direction. The second elongate members 412 include concave partially cylindrical upper surfaces. This substrate 410 is formed into a speaker by placing a piezoelectric film onto the upper surface of the substrate 410, making the piezoelectric film follow the profile of the upper surface of the substrate 410, and fixing the film to the first elongate members 411.

As in the previous embodiments, the film may be forced to follow the profile of the substrate 410 using a cover (not shown) which is brought towards the substrate 410 to sandwich the film, and permanently connected to the substrate 410 to clamp the film against the first elongate members 410.

- 5 Alternatively, it may be done using a cover which is brought towards the film to sandwich the film and press the film against adhesive provided on the first elongate members 411, so that the film becomes bonded there. In the second case, the cover may be optionally be removed after the film is bonded to the substrate 410. Otherwise, the cover may be provided with apertures for
- 10 allowing sound generated by the film to be transmitted. In either case, the film should not be excessively stressed while it is clamped/bonded to the substrate. The first elongate members 411 constitute the fixing portions of the substrate 410. The substrate 410 may also function as a mechanical damper to increase the bandwidth of the speaker.
- 15 Although only four embodiments of the invention have been described, 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, 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
- 20 increase the conversion efficiency from ultrasonic energy to audible sound.

Claims

1. A speaker unit for a sound generation system, the speaker unit comprising:

5 a flexible piezoelectric film having electrodes for applying a voltage signal to the film, and

a substrate which is fixed to the film at multiple elongate fixing portions of the substrate, the elongate fixing portions being spaced apart by regions in which the film is not fixed to the substrate, the substrate maintaining the film in a configuration including corrugations, the elongate fixing portions lying
10 between corresponding pairs of corrugations and extending parallel to the corrugations.

2. A speaker unit according to claim 1 in which the film is adhered to the substrate at the fixing portions.

3. A speaker unit according to claim 1 in which the film is clamped at the
15 fixing portions between the substrate and a cover element.

4. A speaker unit according to claim 3 in which the cover element includes apertures.

5. A speaker unit according to any preceding claim in which the substrate includes support elements for supporting the corrugations in the film.

20 6. A speaker unit according to claim 5 which the support elements include a surface which is part of a respective cylinder.

7. A speaker unit according to claim 5 or claim 6 in which the support elements are convex.

8. A speaker unit according to claim 7 when dependent on claim 3 in which the cover includes concave portions located in register with the support elements.
9. A speaker unit according to claim 5 or claim 6 in which the support
5 elements are concave.
10. A speaker unit according to any preceding claim in which the film includes three or more electrodes and multiple areas which are independently actuable by applying voltage signals between corresponding pairs of the electrodes.
- 10 11. A speaker unit according to any preceding claim further including at least one sound absorbing element located on the same side of the film as the substrate.
12. A sound generation system including an oscillator for generating an oscillating signal, a modulating unit for modulating the ultrasonic signal
15 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 electrodes.
13. A method of producing a speaker unit, the method including locating a
20 flexible piezoelectric film between a substrate and a cover, bringing the substrate and the cover together, thereby flexing the film to induce corrugations in the film, and fixing the film to at elongate fixing portions of the substrate located between the corrugations and extending parallel to the corrugations.
- 25 14. A method according to claim 13 in which the fixing portions of the substrate include an adhesive, whereby the film is adhered to the fixing portions when the film is pushed against the fixing portions by the cover.

15. A method according to claim 14 in which following the fixing the cover is removed.
16. A method according to claim 13 in which the cover is secured to the substrate, and the film is clamped between the cover and the fixing positions
5 of the substrate.
17. A method according to any of claims 13 to 16 in which, while the substrate and cover are brought together, a shaping member contacts the film to ensure that the film adopts the corrugated configuration, the method including subsequently removing the shaping member.
- 10 18. A method according to any of claims 13 to 17 further including locating at least one sound absorbent material on the same side of the film as the substrate.
19. A speaker unit for a sound generation system, the speaker unit comprising:
- 15 a flexible piezoelectric film having electrodes for applying a voltage signal to the film, and
- a substrate which is fixed to the film at multiple elongate fixing portions of the substrate which maintain the film in a corrugated configuration, the elongate fixing portions being parallel to the corrugations and mutually spaced
20 apart in the direction on the surface of the substrate transverse to the corrugations.