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(54) ULTRASOUND PROBE DEVICE AND METHOD OF OPERATION

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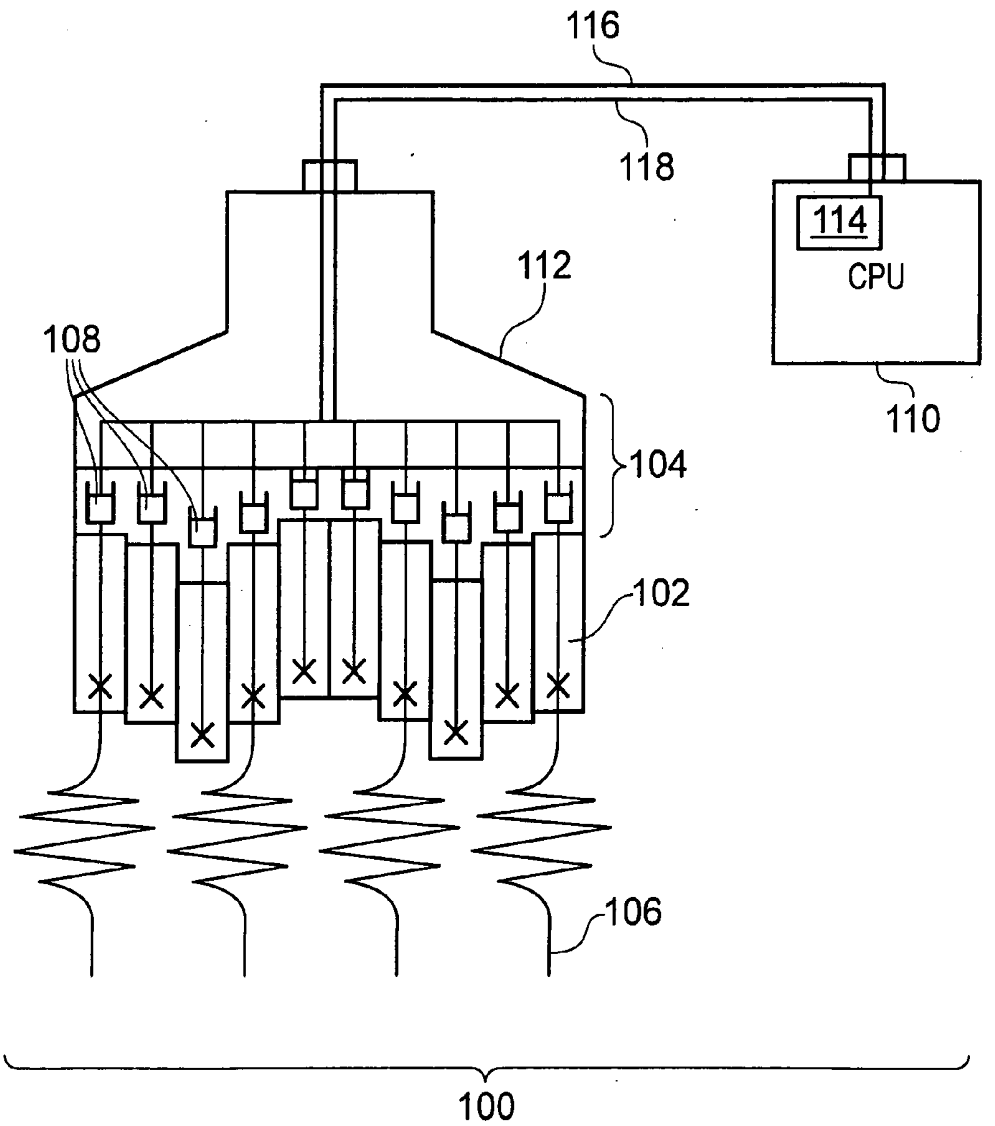
(57) ABSTRACT

The present invention relates to an ultrasound probe device. A device **100** embodying the present invention comprises an array of transducers **102**, at least one of which is movable relative to at least one of the other transducers **102**. Preferably, the or each movable transducer may be movable relative to at least one of the other transducers along one axis of movement only. This axis of movement is preferably parallel with an initial direction of travel of emitted ultrasound waves relative to the device.



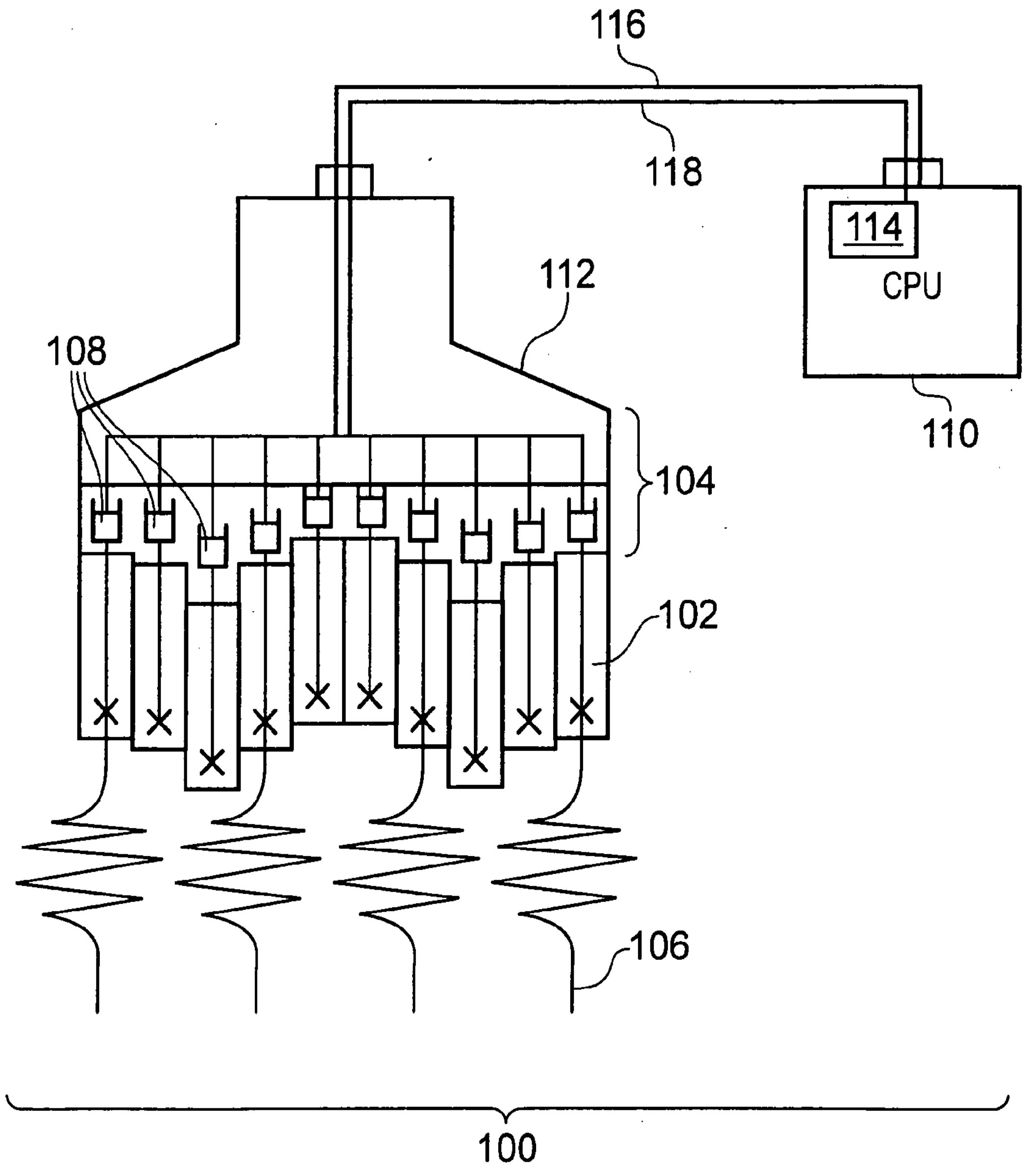


FIG. 1

ULTRASOUND PROBE DEVICE AND METHOD OF OPERATION

[0001] The present invention relates to an ultrasound probe device and a method of using the same.

[0002] Ultrasound is used in medicine both as a primary imaging tool and in conjunction with other tools. It can be used to produce images of cross sections of regions of interest to clinicians. Ultrasound cannot penetrate bones or pockets of gas so its main function is in imaging soft tissue. Ultrasound is preferred to alternative imaging tools because it does not use ionising radiation, it produces images in real time, and it can be used to give quantitative images of blood flow.

[0003] An ultrasound device operating in a conventional "echo" mode works by transmitting a pulse of sound into a region of interest and detecting the echoes received back from within the region. The sound is transmitted from an array of piezoelectric elements, known as the aperture. The received echoes, which are detected by the same piezoelectric elements used for transmission, are used to produce either a 3-dimensional (3-d), or more usually a 2-dimensional (2-d), map of tissue echogenecity.

[0004] Medical ultrasound is particularly useful for providing images of tumours in the breast since these are generally surrounded entirely by soft tissue (no bones or lungs between them and the skin) and are not buried too deeply in the body (beyond the effective range of an ultrasound pulse).

[0005] The homogeneous wave equation predicts that pressure (sound) waves travelling in a homogeneous medium are non-dispersive and travel in straight lines through the medium. Body tissue, however, is not a homogeneous medium—it contains interfaces between regions with different bulk properties (e.g. cancerous lesions are less compressible than the healthy tissue surrounding them). Furthermore, small fluctuations in the values of density and compressibility about their bulk values are seen within small regions. Both types of inhomogeneity redirect some of the energy of the pressure waves back to the aperture, allowing the formation of ultrasound images. This energy is redirected either via reflection at tissue boundaries, or via scattering from features with dimensions similar to the wavelength of the pressure wave.

[0006] An ultrasound image is made up of a combination of sharp lines seen from reflection at tissue boundaries, and the textured speckle generated by scattering elsewhere in the image. Hence the image is inherently noisy (although in medical ultrasound the image and the noise are effectively one and the same), making it difficult to pick out the features of interest as the speckle reduces the contrast between a tumour and the surrounding healthy tissue. One of the methods with the most potential to increase the contrast appears to be elastography (elasticity imaging).

[0007] The aim of elastography is to construct an image of the mechanical properties of a region of interest. Fundamentally these properties are a measure of the amount of deformation (strain) an object experiences in response to the application of a known force (stress). Hence, ultrasound elasticity imaging requires at least two ultrasound images of the region of interest. For more accuracy a series of intermediate images must also be used. Each subsequent image must be registered to the first image in order that a series of displacement fields can be estimated. Mathematical models can then be used to estimate the mechanical properties of the tissue and a stiffness field can be generated.

[0008] It is desirable to acquire sufficient data to ensure that only one stiffness field is compatible with the observed displacement fields. In general, in order to uniquely solve the equations that determine the tissue stiffness field it is necessary to specify boundary conditions on the stiffness. However, for a general region of tissue we have no a priori way of determining these boundary conditions. The theory tells us that (if the tissue is assumed to be linearly elastic) four linearly independent displacement fields are needed in order to eliminate the need for boundary conditions for a 2-d image (using a linear array probe) and three fields for a 3-d image (using a rectangular array).

[0009] Conventionally, generating displacement fields is achieved by pressing the ultrasound probe into the tissue with varying levels of force. For example, United States Patent Application Publication US2007032726 discloses an ultrasound probe including a pressing mechanism for applying a pressing operation perpendicularly to the ultrasound wave transmit/receive surface. However, the resulting displacement fields are not linearly independent (if the tissue is assumed to be linearly elastic then pressing the probe twice as far into the tissue will simply double the displacements everywhere in the region of interest). It is therefore desirable to find a way of generating linearly independent displacement fields in an appropriate manner.

[0010] An ultrasound probe device embodying a first aspect of the present invention comprises an array of transducers, wherein at least one of the transducers is movable relative to at least one of the other transducers of the array. This configuration enables the probe to be used to generate linearly independent displacement fields from a sequence of images obtained without removing the probe from a contact surface of a region of interest.

[0011] Desirably, in an ultrasound probe device according to an embodiment of the present invention, the or each movable transducer is movable relative to at least one of the other transducers along one axis of movement only. Preferably, in the case where the movable transducers are a plurality of transducers, the axes of movement are mutually parallel.

[0012] In a device embodying the present invention it is desirable for each axis of movement to be parallel with an initial direction of travel of emitted ultrasound waves relative to the device.

[0013] Another embodiment of the present invention further comprises a driving means for applying a driving force to at least one of the transducers thereby to move those transducers along their respective axis of movement.

[0014] The driving means according to an embodiment of the present invention comprises a plurality of actuators associated with respective ones of the plurality of transducers, each actuator being operable to apply a driving force to an associated one of the transducers thereby to move its associated transducer along its respective axis of movement.

[0015] In another embodiment of the present invention the or each movable transducer is configurable to change a contact profile of the device by changing the position of the end of the or each movable transducer operable to emit ultrasound waves relative to the end operable to emit ultrasound waves of at least one other transducer.

[0016] A device according to an embodiment of the present invention further comprises a controlling means for controlling the driving means as to the extent to which the or each movable transducer should be moved, and when the movement should occur.

[0017] In one embodiment of the present invention the array of transducers is a linear array having only one row of transducers. In another embodiment, the array of transducers is arranged as a 2-dimensional array having more than one row of transducers.

[0018] In a device embodying the present invention the controlling means is operable to instruct the transducers to emit ultrasound pulses in a manner that they either converge or diverge as they move away from the transducers.

[0019] An embodiment according to a second aspect of the present invention is a method of using an ultrasound probe device to carry out an elastography imaging process comprising at least two image taking steps of taking an ultrasound image using an ultrasound probe device comprising an array of transducers, wherein at least one of the transducers is movable relative to at least one of the other transducers of the said array, following a first such image taking step, each subsequent image taking step is preceded by a step of changing the configuration of the transducers by enacting movement of at least one movable transducer relative to at least one other transducer of the array, and maintaining contact between the ultrasound probe device and a region of interest throughout the entire process.

[0020] In another embodiment of a second aspect of the present invention, the step of changing the configuration of the transducers is controlled by communication between the transducers and a controlling means via a control communication means **118**. This control communication means **118** could take the form of, for example, a wire or set of wires running from the CPU **110** and into the outer casing **112** via an entry at the opposite end of the device to the contact profile, and then connecting to the components as required within the outer casing **112**.

[0021] A further embodiment of a second aspect of the present invention comprises generating a linearly independent displacement field from each image taking step and then performing a calculation step to generate a stiffness field compatible with the obtained linearly independent displacement fields.

[0022] Reference will now be made, by way of example, to the accompanying drawing, in which:

[0023] FIG. **1** is a diagram showing an ultrasound probe device embodying the present invention.

[0024] As shown in FIG. **1**, an ultrasound probe device **100** embodying the present invention comprises an array of piezoelectric transducers **102**. In the present embodiment, each of the transducers is movable along an axis parallel to the initial direction of travel of emitted sound waves relative to the device, but a device embodying the present invention may comprise an array of transducers in which fewer of the transducers are movable, for example an array in which only one is movable. Preferably, the transducers **102** are several centimeters or more in length and approximately a millimeter in diameter, and are positioned parallel to one another in the array so that, when viewed end-on, the centre to centre separation of neighbouring transducers **102** is of the order of a millimeter.

[0025] The array may be a linear array comprising only one row of perhaps up to a hundred transducers **102**, or the array may take a different form, for example a rectangular or approximately circular array with each row comprising tens or hundreds of transducers **102**.

[0026] A device embodying the present invention also comprises a driving means **104** connected and arranged for bringing about movement of the transducers. In the present embodiment, the driving means **104** is arranged at one end of the array of transducers **102**. The driving means **104** may be an array of actuators **108**, each associated with one or more transducers **102**. There are numerous possibilities as to the exact nature of these actuators **108**, but they could be for example, electromechanical, or they could be pneumatic or hydraulic.

[0027] In a device embodying the present invention the entire assembly of transducers **102** and the driving means **104** are at least partially housed in an outer casing **112**. The distal (when viewed with respect to the driving means **104**) ends of the transducers **102** may be exposed, or the distal end of the entire array may be covered by a flexible sheath. The external shape formed by the combination of the distal ends of the array of transducers **102** in combination is defined herein as a contact profile of the device, i.e. the profile of the device which contacts the subject undergoing ultrasound imaging. The movable nature of the transducers means that there will be discontinuities in the contact profile of the device. It is desirable to keep these discontinuities as small as possible, hence a large number of transducers is preferable.

[0028] A device embodying the present invention further comprises a controlling means **114**. The controlling means **114** may be a CPU **110**, or a component of a CPU **110**, and may or may not be housed within the outer casing **112**. Means of communication **118** between the controlling means **114** and the driving means **104** are provided. In the case where the controlling means **114** is not housed within the outer casing **112**, the means of communication could take the form of, for example, a wire or set of wires running from the controlling means **114** and into the outer casing **112** via an entry at the opposite end of the device to the contact profile, and then connecting to the components as required within the outer casing **112**. Each actuator **108** and each transducer **102** has some means of communication with the controlling means **114**.

[0029] A device embodying the present invention comprises a CPU **110**. Means of communication between the CPU **110** and the transducers **102** are provided via a CPU communication means **116**. This CPU communication means **116** could take the form of, for example, a wire or set of wires running from the CPU **110** and into the outer casing **112** via an entry at the opposite end of the device to the contact profile, and then connecting to the components as required within the outer casing **112**. Each transducer **102** has means of communication with the CPU **110**.

[0030] Each transducer **102** is operable to receive an electrical signal from the controlling means **114**, and to convert it into a sound wave to be emitted from the distal end of the transducer **102** into a region of interest. Medical ultrasound devices usually emit sound waves with a frequency between 2 and 18 MHz. In a device for imaging a breast, a typical ultrasound pulse might have a frequency in the range 7.5-12 MHz. The controlling means **114** can slightly stagger the times at which each of the transducers **102** emit their sound waves in order to focus the overall wave pulse (this is known as beam forming). An alternative method for focussing the direction and depth of the beam is to use a phased array technique, whereby the controlling means **114** is able to manipulate the relative phases of the emitted waves.

[0031] The emitted sound waves can then be reflected or scattered by tissue boundaries or small features in the region of interest. This reflected and scattered sound is known as the echo. Any portion of the echo incident upon a piezoelectric transducer **102** of the probe device is then converted back into an electrical signal and sent via the communication means to the CPU **110**. The CPU **110** can then generate an ultrasound image based on the intensity (calculated for example, from the amplitude of the electrical signal) and timing of the electrical signal received from each transducer.

[0032] One embodiment of the present invention is operable to emit ultrasound pulses from each, or groups of, transducer(s) in sequence, and an image is built up based on the timings of echoes received from the pulses. This is especially useful in an embodiment whereby the emitted ultrasound waves are either deflected before entry into the region of interest, or are emitted in a manner such that they converge or diverge as they travel away from the probe. It may be desirable to emit ultrasound waves in a manner such that they converge to either focus the waves on a small region of interest or in order to increase the resolution of the image. Conversely, an image of a larger region of interest with a lower resolution can be obtained by emitting waves in a manner such that they diverge from the probe device.

[0033] In an embodiment of the present invention, the driving means **104** is operable to move one or more of the transducers **102** relative to at least one or more other transducers **102**. Any movement of a transducer **102** relative to another performed by the driving means **104** is along the axis of movement of the or each respective transducer. This axis of movement is parallel to the direction in which an emitted ultrasound wave would travel relative to the device. Moving the transducers **102** in this way is carried out by the driving means **104** in accordance with instructions received from the controlling means **114**. When they are not moving, the transducers **102** are fixed in position. This enables the controlling means **114** to engender a change in the contact profile of the device.

[0034] In an embodiment of the present invention the driving means **104** comprises a plurality of actuators **108**. These actuators **108** are each associated with one, or a group of, transducers **102**. When an appropriate instruction is received from the controlling means **114**, the actuators **108** are operable to apply a driving force to their associated transducer(s) **102**. When the transducers **102** are not being moved by their respective actuator, their positions relative to one another are fixed. In this way, the controlling means **114** is operable to dictate the extent to which each actuator **108** should move its associated transducer or transducers **102** thereby to engender a change in the contact profile of the device.

[0035] The number of possible contact profile shapes is limited by the extent to which the or each movable transducer can move along its axis of movement, and the number of points within this range of movement at which its position can be fixed. The number of different configurations of contact profile N is given by $N=p^t$, where t is the number of movable transducers **102** and p the number of potential fixed positions within the range of movement of the or each movable transducer. Although the number of potential contact profiles is large (for example 100 movable transducers **102** each with a choice of 10 fixed positions gives 10^{100} possible contact profiles), it is preferable that gradients on the profile whilst obtaining an image are shallow.

[0036] In one embodiment of the present invention, the end of the outer casing **112** distal from the contact profile forms what is effectively a handle. Depending on the dimensions of the device, the outer casing **112** may taper from a wider cross section at the contact profile end into a thinner cross section at the distal end. The handle should be formed such that a human operator may exert a firm grip on the device. In an alternative embodiment, the handle may be suitable to be held firmly by a mechanical brace or fixed in position by some other means.

[0037] Embodiments of the present invention are operable to perform elastography (elasticity imaging) of human tissue. When used in this way, a water based gel is applied to the area skin on which the contact profile of the device is to be placed. This reduces the portion of the ultrasound pulse reflected at the device/skin boundary, or the device/air/skin boundaries in the case where the device is not in immediate contact with the skin. In this way the amount of the ultrasound pulse entering the region of interest is optimised.

[0038] Throughout the entire elastogaphy imaging process, the device should be held so that the position or angle of the contact profile relative to the region of interest is maintained. The device should be held firmly so that approximately constant pressure is applied to the region of interest. At the beginning of the process, an initial ultrasound image of the region of interest is obtained. The transducers **102** are then moved and fixed in their new position according to instructions issued to the driving means **104** from the controlling means **114**, so that the contact profile of the device is changed. The contact profiles used in an entire imaging process should be different from one another. The region of interest is then re-imaged. This cycle of changing contact profile and imaging can continue a number of times until the process is deemed to be complete. This number may be pre-determined, or may be decided during the imaging process by the operator according to the quality of images obtained.

[0039] For each ultrasound image that can be referenced back to either the initial image, or a nominal reference image (form the same sequence), the CPU **110** is operable to generate displacement fields. Displacement estimation is an active field of research, though current methods that may be used by an embodiment of the present invention include differential methods, frequency based methods, and block-matching displacement estimation. Because of the different contact profile used for each image, the displacement fields so obtained are linearly independent from one another. Based on these displacement fields, the CPU **110** is operable to generate a stiffness field (image).

[0040] Embodiments of the present invention use parameter recovery methods to obtain a stiffness field from a sequence of displacement fields. As mentioned previously, theoretically (if the tissue is assumed to be linearly elastic) four linearly independent displacement fields are needed in order to eliminate the need for boundary conditions for a 2-d image (using a linear array probe) and three fields for a 3-d image (using a rectangular or approximately circular array). Several parameter recovery methods are available. In an embodiment of the present invention, a method using linear elasticity models for the soft tissue in the region of interest and finite element methods to determine tissue properties from given displacement fields is preferred.

[0041] Oil and gas exploration represent another potential application of a device embodying the present invention. The physical dimensions of such a device would probably be significantly larger than those of a device intended for medical use. The use of ultrasound in oil and gas exploration is an example of a surface seismic method. These are methods in which ultrasound waves are transmitted into the ground above a region of interest, and the resultant echoes can be used to construct an image of the sub-surface geology.

1. An ultrasound probe device comprising;

an array of transducers, wherein at least one of the transducers is movable relative to at least one of the other transducers of the said array.

2. The ultrasound probe device according to claim **1**, wherein:

each said movable transducer is movable relative to said at least one of the other transducers along one axis of movement only.

3. The ultrasound probe device according to claim **2**, wherein said movable transducers comprise a plurality of transducers having respective axes of movement which are mutually parallel.

4. The ultrasound probe device according to claim **2** wherein each axis of movement is parallel with an initial direction of travel of emitted ultrasound waves relative to the device.

5. The ultrasound probe device according to claim **2** further comprising:

driving means for applying a driving force to at least one of the transducers thereby to move said at least one of the transducers along the respective said axis of movement.

6. The ultrasound probe device according to claim **5**, wherein the driving means comprises a plurality of actuators associated with respective ones of the plurality of transducers, each actuator being operable to apply a driving force to an associated one of the transducers thereby to move said associated transducer along its respective axis of movement.

7. The ultrasound probe device according to claim **1**, wherein:

each movable transducer is configurable to change a contact profile of the device by changing the position of each movable transducer operable to emit ultrasound waves relative to the end of at least one other transducer.

8. The ultrasound probe device according to claim **1**, further comprising:

controlling means for controlling the driving means as to the extent to which each movable transducer is moved, and when the movement should occur.

9. The ultrasound probe device according to claim **1**, wherein:

the array of transducers is a linear array having only one row of transducers.

10. The ultrasound probe device according to claim **1**, wherein:

the array of transducers is arranged as a 2-dimensional array having more than one row of transducers.

11. The ultrasound probe device according to claim **8**, wherein:

the controlling means is operable to instruct the transducers to emit ultrasound pulses in such a manner that they either converge or diverge as they move away from the transducers.

12. A method of using an ultrasound probe device to carry out an elastography imaging process, which method comprises:

at least two image taking steps of taking an ultrasound image using an ultrasound probe device, which device comprises an array of transducers, wherein at least one of the transducers is movable relative to at least one of the other transducers of said array;

following a first such image taking step, each subsequent image taking step is preceded by a step of changing the configuration of the transducers by enacting movement of at least one movable transducer relative to at least one other transducer of the array; and

maintaining contact between the ultrasound probe device and a region of interest throughout the entire elastography imaging process.

13. A method according to claim **12**, wherein the changing the configuration of the transducers is controlled by communication between the transducers and a controlling means.

14. A method according to claim **12** or **13**, further comprising:

generating a linearly independent displacement field from each image taking step; and

performing a calculation step to generate a stiffness field compatible with the obtained linearly independent displacement field.

15. (canceled)

16. (canceled)

17. The ultrasound probe device according to claim **3**, wherein the, or each, axis of movement is parallel with an initial direction of travel of emitted ultrasound waves relative to the device.

18. The ultrasound probe device according to claim **3**, further comprising:

driving means for applying a driving force to at least one of the transducers thereby to move said at least one of the transducers along the respective said axis of movement.

19. The ultrasound probe device according to claim **4**, further comprising:

driving means for applying a driving force to at least one of the transducers thereby to move said at least one of the transducers along the respective said axis of movement.

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