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(54) **MULTIPLE APERTURE ULTRASOUND ARRAY ALIGNMENT FIXTURE**

AUSRICHTUNGSVORRICHTUNG FÜR ULTRASCHALL-ARRAY MIT MEHREREN APERTUREN

ACCESSOIRE D'ALIGNEMENT DE RÉSEAU ULTRASONIQUE À OUVERTURES MULTIPLES

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EP 2 419 022 B1

Description

FIELD OF THE INVENTION

[0001] The present invention relates generally to imaging techniques used in medicine, and more particularly to medical ultrasound, and still more particularly to an apparatus for producing ultrasonic images using multiple apertures.

BACKGROUND OF THE INVENTION

[0002] In order to insonify the body tissues, a beam formed either by a phased array or a shaped transducer is scanned over the tissues to be examined. Traditionally, the same transducer or array is used to detect the returning echoes. This design configuration lies at the heart of one of the most significant limitations in the use of ultrasonic imaging for medical purposes; namely, poor lateral resolution. Theoretically, the lateral resolution could be improved by increasing the aperture of the ultrasonic probe, but the practical problems involved with aperture size increase have kept apertures small and lateral resolution poor. Unquestionably, ultrasonic imaging has been very useful even with this limitation, but it could be more effective with better resolution.

[0003] In the practice of cardiology, for example, the limitation on single aperture size is dictated by the space between the ribs (the intercostal spaces). For scanners intended for abdominal and other use, the limitation on aperture size is not so obvious, but it is a serious limitation nevertheless. The problem is that it is difficult to know the exact position of the elements of a large apparatus with multiple and separate physical points of contact ("footprints") on the patient. For optimum performance, all of the separated transmit and receive elements should be in the same scan plane. In addition, each element position must be known to within 1/10 wavelength (for example, .03 mm at 3 MHz). With conventional ultrasound probes, regardless of array vertical displacement or integration (e.g. 1.5D or 2D), there has never been a need to solve alignment and position issues between multiple arrays or multiple individual elements. The methods and apparatus included here teach how to solve these problems for Universal Multiple Aperture ultrasound probes.

[0004] In constructing and maintaining a Universal Multiple Aperture Probe using a combination of two or more individual arrays, attention must be paid to each array's ultrasound beam displacement relative to a central array Z axis. The displacement or rotational axes referred to are X, Y and Z. X varies about the longitudinal array axis, Y varies about the central array axes, also termed twist, and Z varies about the transverse or lateral array axis. A fixture and method for measuring the variation of each array was developed and implemented.

[0005] Element position is equally important as displacement from the central array Z axis. The positional relationship of each array element to every other element needs to be established within an individual array and from array to array.

[0006] The type of crystal used in each array is irrelevant. That is, any one, one and a half, or two dimensional crystal arrays (ID, 1.5D, 2D, such as a piezoelectric array) and all types of Capacitive Micromachined Ultrasonic Transducers (CMUT) can be utilized in multi-aperture configurations.

[0007] US 5,230,339 discloses a test system for evaluating the performance of ultrasonic examination equipment including ultrasonic imaging systems.

[0008] The article "Considerations for Using Phased Array Ultrasonics in a Fully Automated Inspection System" by V A Kramb et al in AIP Conference Proceedings discloses a fully automated ultrasonic inspection system for the detection of defects in gas turbine engine components.

SUMMARY OF THE INVENTION

[0009] The present invention provides a system and method for measuring and aligning the positions of transducer elements in a multi-aperture ultrasound probe according to claims 1 and 11.

[0010] The present invention relates to a system for measuring and aligning the positions of transducer elements in a multi-aperture ultrasound probe, comprising an alignment assembly configured to hold a plurality of transducer elements, a test block, an ultrasonic sensor configured to receive ultrasonic pulses through the test block from at least one of the plurality of transducer elements, and a controller configured to evaluate data from the ultrasonic sensor and provide transducer calibration data.

[0011] In some embodiments, the test block comprises a tank filled with a liquid having a known speed of sound. In other embodiments, the test block comprises a tank filled with a gelatinous material having known speed of sound. In additional embodiments, the test block comprises a solid block having a known speed of sound.

[0012] The system can further comprise a signal generator configured to excite at least one of the plurality of transducer elements to transmit ultrasonic pulses. In some embodiments, the signal generator is configured to excite the plurality of transducer elements with a short (wideband) pulse. In other embodiments, the signal generator is configured to excite the plurality of transducer elements with a spread spectrum waveform. In additional embodiments, the signal generator is configured to excite at least one of the plurality of transducer elements with a chirp waveform.

[0013] In one embodiment, the alignment assembly comprises an automated alignment assembly configured to automatically align the plurality of transducer elements based on the transducer calibration data from the controller. The alignment assembly can comprise at least one stepper motor and a stepper motor controller, for example. In some embodiments, the stepper motor controller drives the at least one stepper motor to align the transducer element.

[0014] In other embodiments, the alignment assembly comprises a manual alignment assembly. The manual alignment assembly can include manual controls configured to manipulate the plurality of transducer elements in the x, y, and z axes.

[0015] In some embodiments, the controller runs algorithms configured to detect relative elapsed times to a plurality of receiving transducer elements disposed on the ultrasonic sensor. In other embodiments, the controller runs algorithms configured to compute complete transit times from at least one of the plurality of transducer elements to a plurality of receiving transducer elements disposed on the ultrasonic sensor. The controller runs algorithms configured to compute the relative position of the plurality of transducer elements based on the transducer calibration data.

[0016] In some embodiments, the system further comprises a graphical user interface configured to display the transducer calibration data.

[0017] In other embodiments, the alignment assembly is configured to hold a probe containing the plurality of transducer elements.

[0018] In some embodiments, the ultrasonic sensor includes a plurality of receiving transducer elements.

[0019] In additional embodiments, the controller is configured to digitize and store the received ultrasonic pulses.

[0020] A system for measuring and reporting the positions of transducer elements in a multi-aperture ultrasound probe is also provided, comprising a plurality of transducer elements, a calibration assembly configured to hold the plurality of transducer elements, a test block, an ultrasonic sensor configured to receive ultrasonic pulses through the test block from at least one of the plurality of transducer elements, and a controller configured to evaluate data from the ultrasonic sensor and provide transducer calibration data.

[0021] In some embodiments, the test block comprises a tank filled with a liquid having a known speed of sound. In other embodiments, the test block comprises a tank filled with a gelatinous material having known speed of sound. In additional embodiments, the test block comprises a solid block having a known speed of sound.

[0022] In some embodiments, the calibration assembly is configured to automatically determine the relative positions of the plurality of transducer elements based on the transducer calibration data from the controller.

[0023] In one embodiment, the controller runs algorithms configured to detect relative elapsed times to a plurality of receiving transducer elements disposed on the ultrasonic sensor. In other embodiments, the controller runs algorithms configured to compute complete transit times from the relative elapsed times. The controller runs algorithms configured to compute the relative position of the plurality of transducer elements based on the transducer calibration data.

[0024] In some embodiments, the system further comprises a graphical user interface configured to display the transducer calibration data.

[0025] In another embodiment, the system further comprises memory in the multi-aperture ultrasound probe configured to record the transducer calibration data.

[0026] A method is also provided for measuring and aligning the positions of transducer elements in a multi-aperture ultrasound probe, comprising mounting a plurality of transducer elements in an alignment assembly, transmitting ultrasonic pulses through a test block from at least one of the plurality of transducer elements, receiving the ultrasonic pulses with an ultrasonic sensor, and evaluating the received ultrasonic pulses from the ultrasonic sensor with a controller to provide transducer calibration data.

[0027] In some embodiments, the method further comprises aligning the plurality of transducer elements based on the transducer calibration data.

[0028] In other embodiments, the method comprises automatically aligning the plurality of transducer elements based on the transducer calibration data. In other embodiments, the method comprises manually aligning the plurality of transducer elements based on the transducer calibration data.

[0029] In some embodiments, the controller runs an algorithm configured to detect relative elapsed times to a plurality of receiving transducer elements disposed on the ultrasonic sensor. In other embodiments, the controller runs an algorithm configured to compute complete transit times from the transducer element to a receiving transducer element disposed on the ultrasonic sensor. The controller runs an algorithm configured to compute the relative position of the plurality of transducer elements based on the transducer calibration data.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] In the drawings:

Figure 1 illustrates a two-aperture system.
Figure 2 illustrates a three-aperture system.
Figure 3 is a schematic diagram showing a possible fixture for positioning an omni-directional probe relative to the

main probe.

Figure 4 is a schematic diagram showing a non-instrumented linkage for two probes.

Figure 5 is a block diagram of the transmit and receive functions where a three array Multiple Aperture Ultrasound Transducer and the associated MAUI electronics are used in conjunction with a host ultrasound machine. In this embodiment, the center probe is used for transmit only and mimics the normal operation of the host transmit probe.

Figure 5a is a block diagram of the transmit and receive functions where a two array Multiple Aperture Ultrasound Transducer and the associated MAUI electronics are used as an add-on to a host ultrasound machine, primarily for cardiac applications, with an add-on instrument. In this case, one probe is used for transmit only and mimics the normal operation of the host transmit probe, while the other probe operates only as a receiver.

Figure 6 is a block diagram of the transmit and receive functions where a Multiple Aperture Ultrasound Transducer is used in conjunction with only a Multiple Aperture Ultrasonic Imaging (MAUI) device. The stand-alone MAUI electronics control all elements on all apertures. Any element may be used as a transmitter or omni-receiver, or grouped into transmit and receive full apertures or even sub-arrays. In this figure the insonification emanates from the central aperture, aperture 2 of 3 apertures.

Figure 6a depicts the insonification emanating from other than center aperture, in this figure Aperture 3 of 3.

Figure 6b is an illustration of two apertures being used a Multiple Aperture Ultrasound Transducer is used in conjunction with only a Multiple Aperture Ultrasonic Imaging (MAUI) device. In this figure the insonification emanates from aperture 2 of 2.

Figure 6c is an illustration of two apertures being used a Multiple Aperture Ultrasound Transducer is used in conjunction with only a Multiple Aperture Ultrasonic Imaging (MAUI) device. In this figure the insonification emanates from aperture 1 of 2.

Figure 7a is a top view of the precision array carrier with six adjustment screws and an array installed.

Figure 7b is a side view showing the longitudinal axis adjustment of an array in the precision array carrier being supported by the array-centering gasket.

Figure 7c is an end view showing the transverse axis adjustment of the array in the precision array carrier being supported by the array-centering gasket.

Figure 8a is a top view of the precision array carrier.

Figure 8b is a side (longitudinal) view of the precision array carrier.

Figure 8c is an end (lateral) view of the precision array carrier.

Figure 9a is a top view of the precision array carrier with a centering gasket in place.

Figure 9b is a side view (longitudinal) of the precision array carrier with a centering gasket in place.

Figure 9c is an end view (lateral) the precision array carrier with a centering gasket in place.

Figure 9d is a bottom view of the precision array carrier with a centering gasket in place.

Figure 10a is a top view of the array in the precision array carrier during a counter-clockwise rotational axis adjustment.

Figure 10b is a top view of the array in the precision array carrier during a clockwise rotational axis adjustment.

Figure 11 shows an end view of a precision array carrier 2150 installed on a tissue equivalent phantom 2182 and ready to transmit and receive during alignment.

Figure 12 shows a side view of the phantom 2182 with the ends of the targets 2167 visible.

Figure 13a is a top view of a carrier assembly with arrays installed (to become a precision carrier array assembly) and aligned within a precision transducer receptacle and stabilized with an acoustic damping material.

Figure 13b is a side view of a precision array carrier with arrays installed (to become a precision carrier array assembly) and aligned within a precision transducer receptacle and stabilized with an acoustic damping material.

Figure 13c is an end view of a precision carrier array with arrays installed (to become a precision carrier array assembly) and aligned within a precision transducer receptacle and stabilized with an acoustic damping material.

Figure 14a is a top view of a precision carrier array with arrays installed and aligned within a precision transducer head receptacle, the acoustic damping material has set and alignment screws have been removed.

Figure 14b is a side view of a precision carrier array assembly with arrays installed and aligned within a precision transducer head receptacle, the acoustic damping material has set and alignment screws have been removed.

Figure 14c is an end view of a precision carrier array with arrays installed and aligned within a precision transducer head receptacle, the acoustic damping material has set and alignment screws have been removed.

Figure 15 shows a precision transducer receptacle or nose piece and three precision carrier array assemblies seated atop the transducer guides.

Figure 16 shows the precision transducer receptacle or nose piece and three precision carrier array assemblies as in Figure 16, and an ultrasound transducer array seated in each transducer guide of the nose piece.

Figure 17 is a drawing using three independent probes and their installed arrays or transducers. This illustration represents the positional nomenclature and array element numbering conventions.

Figure 18A shows the Precision Stage Assembly and sections that control movement in three different axes.

Figure 18B shows the controls for the Precision Stage Assembly.

Figure 19a depicts is an enclosure containing Right and Left Axial Hydrophones and a Transverse Hydrophone.

Figure 19b depicts the dual Axial Hydrophones from the side and illustrates the angular orientation of the Transverse Hydrophone.

Figure 20 is a representation of probes attached to the precision stage assemblies on top of a fluid filled tank, and well above the hydrophone assembly.

Figure 21a is a graphic of basic geometry used to begin the conversion of distance difference into total distance.

Figure 21b is a graphic of the detailed geometry used to begin the conversion of distance difference into total distance allowing for the precision location of array element using three hydrophones.

Figure 22 illustrates a nose piece containing three separate arrays after it is installed into a Multiple Aperture Transducer. This figure includes the transducer specific calibration chip, the transmit synchronization module and probe position displacement sensor.

Figure 23a is a representation of the graphical user interface or GUI developed to allow for the precise location of elements of multiple arrays under test.

Figure 23b depicts an array of elements under test with the ultrasound beam in the center of the transverse hydrophone, centered between the left and right hydrophones with the results displayed on the graphical user interface.

Figure 23c is a representation of an array under test where its beam is on center but with the array to the right of center with the results displayed on the graphical user interface.

Figure 23d is a representation of an array under test that is physically on the center axis, but has its beam is to the left of center with the results displayed on the graphical user interface.

Figure 24 is a representation of the automatic precision stage assembly and its major components.

Figure 25 is a representation using three arrays and three precision alignment stage assemblies showing their physical placement during testing.

Figure 26a is an illustration of an Onboard Calibration and Quality Assurance fixture mounted to the side of the MAUI standalone system. This illustration depicts a MAUI Radiology probe being evaluated.

Figure 26b illustrates the Onboard Calibration and Quality Assurance fixture evaluating a MAUI Cardiac probe.

DETAILED DESCRIPTION OF THE INVENTION

[0031] A Multiple Aperture Ultrasound Imaging (MAUI) Probe or Transducer can vary by medical application. That is, a general radiology probe can contain multiple transducers that maintain separate physical points of contact with the patient's skin, allowing multiple physical apertures. A cardiac probe may contain as few as two transmitters and receivers where the probe fits simultaneously between two or more intercostal spaces. An intracavity version of the probe, will space transmit and receive transducers along the length of the wand, while an intravenous version will allow transducers to be located on the distal length the catheter and separated by mere millimeters. In all cases, operation of multiple aperture ultrasound transducers can be greatly enhanced if they are constructed so that the elements of the arrays are aligned within a particular scan plane.

[0032] One aspect of the invention solves the problem of constructing a multiple aperture probe that functionally houses multiple transducers which may not be in alignment relative to each other. The solution involves bringing separated elements or arrays of elements into alignment within a known scan plane. The separation can be a physical separation or simply a separation in concept wherein some of the elements of the array can be shared for the two (transmitting or receiving) functions. A physical separation, whether incorporated in the construction of the probe's casing, or accommodated via an articulated linkage, is also important for wide apertures to accommodate the curvature of the body or to avoid non-echogenic tissue or structures (such as bone).

[0033] Any single omni-directional receive element (such as a single crystal pencil array) can gather information necessary to reproduce a two-dimensional section of the body. In some embodiments, a pulse of ultrasound energy is transmitted along a particular path; the signal received by the omni-directional probe can be recorded into a line of memory. When the process for recording is complete for all of the lines in a sector scan, the memory can be used to reconstruct the image.

[0034] In other embodiments, acoustic energy is intentionally transmitted to as wide a two-dimensional slice as possible. Therefore all of the beam formation must be achieved by the software or firmware associated with the receive arrays. There are several advantages to doing this: 1) It is impossible to focus tightly on transmit because the transmit pulse would have to be focused at a particular depth and would be somewhat out of focus at all other depths, and 2) An entire two-dimensional slice can be insonified with a single transmit pulse.

[0035] Omni-directional probes can be placed almost anywhere on or in the body: in multiple or intercostal spaces, the suprasternal notch, the substernal window, multiple apertures along the abdomen and other parts of the body, on an intracavity probe or on the end of a catheter.

[0036] The construction of the individual transducer elements used in the apparatus is not a limitation of use in multi-aperture systems. Any one, one and a half, or two dimensional crystal arrays (1D, 1.5D, 2D, such as a piezoelectric array) and all types of Capacitive Micromachined Ultrasonic Transducers (CMUT) can be utilized in multi-aperture configurations to improve overall resolution and field of view.

[0037] Transducers can be placed either on the image plane, off of it, or any combination. When placed away from the image plane, omni-probe information can be used to narrow the thickness of the sector scanned. Two dimensional scanned data can best improve image resolution and speckle noise reduction when it is collected from within the same scan plane.

[0038] Greatly improved lateral resolution in ultrasound imaging can be achieved by using probes from multiple apertures. The large effective aperture (the total aperture of the several sub apertures) can be made viable by compensation for the variation of speed of sound in the tissue. This can be accomplished in one of several ways to enable the increased aperture to be effective rather than destructive.

[0039] The simplest multi-aperture system consists of two apertures, as shown in Figure 1. One aperture could be used entirely for transmit elements 110 and the other for receive elements 120. Transmit elements can be interspersed with receive elements, or some elements could be used both for transmit and receive. In this example, the probes have two different lines of sight to the tissue to be imaged 130. That is, they maintain two separate physical apertures on the surface of the skin 140. Multiple Aperture Ultrasonic Transducers are not limited to use from the surface of the skin, they can be used anywhere in or on the body to include intracavity and intravenous probes. In transmit/receive probe 110, the positions of the individual elements T_x1 through T_xn can be measure in three different axes. This illustration shows the probe perpendicular to the x axis 150, so each element would have a different position x and the same position y on the y axis 160. However, the y axis positions of elements in probe 120 would be different since it is angled down. The z axis 170 comes in or out of the page and is very significant in determine whether an element is in or out of the scan plane.

[0040] Referring to Figure 1, suppose that a Transmit Probe containing ultrasound transmitting elements T1, T2, ... Tn 110 and a Receive Probe 120 containing ultrasound receive elements R1, R2, ... Rm are placed on the surface of a body to be examined (such as a human or animal). Both probes can be sensitive to the same plane of scan, and the mechanical position of each element of each probe is known precisely relative to a common reference such as one of the probes. In one embodiment, an ultrasound image can be produced by insonifying the entire region to be imaged (e.g., a plane through the heart, organ, tumor, or other portion of the body) with a transmitting element (e.g., transmit element T_x1), and then "walking" down the elements on the Transmit probe (e.g., T_x2, ... T_xn) and insonifying the region to be imaged with each of the transmit elements. Individually, the images taken from each transmit element may not be sufficient to provide a high resolution image, but the combination of all the images can provide a high resolution image of the region to be imaged. Then, for a scanning point represented by coordinates (i,j) it is a simple matter to calculate the total distance "a" from a particular transmit element T_xn to an element of tissue at (i,j) 130 plus the distance "b" from that point to a particular receive element. With this information, one could begin rendering a map of scatter positions and amplitudes by tracing the echo amplitude to all of the points for the given locus.

[0041] Another multi-aperture system is shown Figure 2 and consists of transducer elements in three apertures. In one concept, elements in the center aperture 210 can be used for transmit and then elements in the left 220 and right 230 apertures can be used for receive. Another possibility is that elements in all three apertures can be used for both transmit and receive, although the compensation for speed of sound variation would be more complicated under these conditions. Positioning elements or arrays around the tissue to be imaged 240 provides much more data than simply having a single probe 210 over the top of the tissue.

[0042] The Multiple Aperture Ultrasonic Imaging methods described herein are dependent on a probe apparatus that allows the position of every element to be known and reports those positions to any new apparatus the probe becomes attached. Figures 3 and 4 demonstrate how a single omni-probe 310 or 410 can be attached to a main transducer (phased array or otherwise) so as to collect data, or conversely, to act as a transmitter where the main probe then becomes a receiver. In both of these embodiments the omni-probe is already aligned within the scan plan. Therefore, only the x and y positions 350 need be calculated and transmitted to the processor. It is also possible to construct a probe with the omni-probe out of the scan plane for better transverse focus.

[0043] An aspect of the omni-probe apparatus includes returning echoes from a separate relatively non-directional receive transducer 310 and 410 located away from the insonifying probe transmit transducer 320 and 420, and the non-directional receive transducer can be placed in a different acoustic window from the insonifying probe. The omni-directional probe can be designed to be sensitive to a wide field of view for this purpose.

[0044] The echoes detected at the omni-probe may be digitized and stored separately. If the echoes detected at the omni-probe (310 in Figure 3 and 410 in Figure 4) are stored separately for every pulse from the insonifying transducer, it is surprising to note that the entire two-dimensional image can be formed from the information received by the one omni. Additional copies of the image can be formed by additional omni-directional probes collecting data from the same set of insonifying pulses.

[0045] In Figure 5, the entire probe, when assembled together, is used as an add-on device. It is connected to both an add-on instrument or MAUI Electronics 580 and to any host ultrasound system 540. The center array 510 can be used for transmit only. The outrigger arrays 520 and 530 can be used for receive only and are illustrated here on top of the skin line 550. Reflected energy off of scatterer 570 can therefore only be received by the outrigger arrays 520 and 530. The angulation of the outboard arrays 520 and 530 are illustrated as angles α_1 560 or α_2 565. These angles can be varied to achieve optimum beamforming for different depths or fields of view. α_1 and α_2 are often the same for outboard arrays, however, there is no requirement to do so. The MAUI Electronics can analyze the angles and accommodate unsymmetrical configurations. Fig. 5a demonstrates the right transducer 510 being used to transmit, and the other transducer 520 is being used to receive.

[0046] Figure 6 is much like Figure 5, except the Multiple Aperture Ultrasound Imaging System (MAUI Electronics) 640 used with the probe is a stand-alone system with its own onboard transmitter (i.e., no host ultrasound system is used). This system may use any element on any transducer 610, 620, or 630 for transmit or receive. The angulation of the outboard arrays 610 and 630 is illustrated as angle α 660. This angle can be varied to achieve optimum beamforming for different depths or fields of view. The angle is often the same for outboard arrays; however, there is no requirement to do so. The MAUI Electronics will analyze the angle and accommodate unsymmetrical configurations.

[0047] In this illustration, transmitted energy is coming from an element or small group of elements in Aperture 2 620 and reflected off of scatterer 670 to all other elements in all the apertures. Therefore, the total width 690 of the received energy is extends from the outermost element of Aperture 1 610 to the outmost element of Aperture 2 630. Fig. 6a shows the right array 610 transmitting, and all three arrays 610, 620 and 630 receiving. Figure 6b shows elements on the left array 610 transmitting, and elements on the right array 620 receiving. Using one transducer for transmit only has advantages with regard to a lack of distortion due to variation in fat layer. In a standalone system, transmit and/or receive elements can be mixed in both or all three apertures.

[0048] Figure 6b is much like Figure 5a, except the Multiple Aperture Ultrasound Imaging System (MAUI Electronics) 640 used with the probe is a stand-alone system with its own onboard transmitter. This system may use any element on any array 610 or 620 for transmit or receive as is shown in Figure 6c. As shown in either Figure 6b or Figure 6c, a transmitting array provides angle off from the target that adds to the collective aperture width 690 the same way two receive only transducers would contribute.

[0049] Embodiments described herein include a precision carrier for the proper alignment of a universal multiple aperture ultrasound transducer. Referring now to Figs. 7a-7c, transducer array 2161 can be already "potted" in its own fixture 2161 with lens 2162 intact. Potting procedures are conventional methods to secure the transducer array to its lens and to the case. Flex circuitry, cabling, and attachment to the larger multiple aperture ultrasound transducer fixture can take place after the potting procedure is complete. A benefit of the invention is that it does not require the same transducers to be utilized during the alignment. Different transducers with different "pots" can be utilized in any location of the alignment fixture thanks to the flexibility of the alignment carrier.

[0050] Figures 8a - 8c provide views of the basic structure and features of embodiments of a precision carrier 2150 for a multiple aperture ultrasound transducer array. Figure 8a shows a top view of a precision array carrier 2150 with six positioning screws 2151. Figure 8b shows a side view of a precision array carrier 2150 having two threaded screw holes 2180 on each side. When positioning screws 2151 are inserted into threaded screw holes (e.g., screw holes 2155 and 2156 in Figure 7b), adjustments may be made to employ longitudinal corrections 2159 to the "seated" array. Figure 8c shows a side view of a precision carrier 2150 with threaded screw holes 2180 located on each end. When positioning screws are inserted into these threaded screw holes, adjustments may be made to employ lateral corrections 2160 to the "seated" array (as illustrated in Figure 7c).

[0051] Figures 9a - 9d show a precision array carrier 2150 with an array-centering gasket 2152 installed. Figure 9a is a top view of the precision carrier 2150, with an array-centering gasket 2152 placed at the bottom of the carrier where the lens 2162 located in the center. Figures 9b - 9d show side, end, and bottom views of the carrier, respectively. The array centering gasket 2152 on the carrier's L shaped shoulder 2181 as illustrated in Figure 7b. In Figure 9b the gasket 2152 extends the entire length of the carrier over the L shaped shoulder 2181. The gasket 2152 extends around the corners of the L shaped shoulder 2181 to cover the ends of the carrier as it illustrated in Figure 9c. The gasket provides the array translational centering and a pivot point for positioning adjustments during operation without interfering with the integrity of the lens 2162. Figure 9d provides a view of the lens 2162, the bottom of the precision carrier array centering gasket 2152, and finally the L shaped shoulder 2181.

[0052] Referring back to Figures 7a - 7c, which show top, end, and side views, respectively of a precision array carrier 2150 with an array 2161 inserted therein. The array 2161 is supported end-to-end by positioning screws 2155 and 2156. The array can be supported from each side by positioning screws 2153, 2154, 2157, 2158 and from the bottom by the array centering gasket 2152. Figure 7b shows the array 2161 in the precision array carrier 2150 being supported by array centering gasket 2152 and ready for longitudinal adjustment. Alternately tightening and loosening positioning screws 2155 and 2156 allows the array 2161 to be adjusted through arc 2159 to correct longitudinal axis errors. Figure 7c shows the array 2161 in the precision array carrier 2150 supported by the array centering gasket 2152 ready for transverse alignment. Alternately adjusting positioning screw pairs 2157, 2158 and 2153, 2154 allow the array 2161 to be corrected for transverse axis errors.

[0053] Figures 10a and 10b show a top views of a precision array carrier 2150 with the array 2161 inserted. Arrows depict, respectively, counter-clockwise and clockwise rotational adjusting by way of selective screw adjustments. Figure 10a shows a tightening of position screws 2153 and 2158 while loosening position screws 2154 and 2157 shifting the array 2161 in a counter-clockwise arc 2165 to correct rotational axis errors. Figure 10b shows a tightening position of screws 2154 and 2157 while loosening position screws 2153 and 2158 to shift the array 2161 in a clockwise arc 2166 to correct rotational axis errors.

[0054] Figure 11 shows an end view of a precision array carrier 2150 installed on a tissue equivalent phantom or test block 2182 and ready to transmit and receive during alignment. A 'phantom' is a structure filled with tissue equivalent material that has a speed of sound characteristics similar to that of human tissue with known voids and reflectors placed at known locations within the phantom. This end view of the phantom shows one embodiment including three targets 2167 in profile view. These targets can be echogenic, very reflective, or anechoic, void of reflection. The top target can be at a pre-determined depth D from the surface of the phantom and the face of array carrier 2150. The other targets can be spaced at distances D1 and D2 from the top target. In some embodiments, the pre-determined depth D can be 100 mm from the top target to the face of the array. The other targets can have D1 and D2 distances of 10 mm, for example. However, any range of depths for the targets 2167 can be used, depending on the desired application of the transducer arrays. The perpendicular targets 2167 serve to assist during the longitudinal adjustment of the array positioning. When correctly positioned, the three targets would be displayed as exactly perpendicular to the front of the array, and further, each target 2167 would be displayed equidistantly one a top the other.

[0055] Figure 12 shows a side view of the phantom 2182 with the ends of the targets 2167 visible. Once transmitting and receiving, a lateral adjustment could be made to the array 2163 in the carrier 2150. The correct alignment is for achieved when all targets are visible above and below the center target 2168.

[0056] Figures 13a - 13c show a precision array carrier 2150 with an array 2161 inserted and aligned, in top, side, and end views, respectively. At this stage an acoustic damping material 2162 can be poured into the gap between the array and the carrier to stabilize the position of arrays 2161. Figure 13b is a side view of the precision array carrier 2150 showing the gap between the array 2161 and the precision array carrier 2150 filled with acoustic damping material 2162. Figure 13c shows the gap between the array 2161 and the precision array carrier 2150 filled with acoustic damping material 2162.

[0057] Figures 14a - 14c show the precision array carrier 2150 with the array 2161 inserted and aligned in top, side, and end views, respectively. The acoustic damping material 2162 has cured and the six alignment screws have been removed. Figure 14b is a side view of the precision array carrier 2150 with the array 2161 inserted, aligned, the acoustic damping material 2162 cured and the position alignment screws removed: At this point, the precision array carrier 2150 with its captured array becomes a precision carrier array assembly 2163.

[0058] Figure 15 shows a multi-aperture ultrasound probe assembly 2183 constructed with precision transducer receptacles surrounded by structural supports 2164. The structural supports 2164 can be constructed out of many hard materials (e.g. metals or plastics) and usually are built into a larger structure such as the probe 2200 in Figure 22. In Figure 15, the three precision carrier array assemblies 2163 are inserted into the precision transducer receptacles 2166.

[0059] Figure 16 shows the multi-aperture probe assembly 2183 having precision transducer receptacles 2166 with the precision array assemblies 2163 each locked into the receptacles, thus completing the construction of the multi-aperture ultrasound probe 2184 having three transducer arrays.

[0060] Figure 22 shows a completed probe 2200 with arrays 1701, 1702, and 1703 fitted in array receptacles and ready for submission to the calibration cycle.

[0061] Alternative apparatus and methods for constructing and aligning multi-aperture ultrasound probes will now be discussed. As described above, variations in the ultrasound beam displacement or rotation of both the insonifying and receiving probes about the x, y and z axes must be detected and corrected. A MAUI alignment fixture for aligning a multi-aperture probe uses one or more precision angular alignment controls, precision stage assemblies that provide for the adjustment, in 6 degrees of freedom of the each array under test.

[0062] One of the great practical difficulties in making multi-aperture imaging systems, as outlined above, is the requirement to precisely align the elements of the multiple arrays. It is well recognized that by increasing the effective aperture of a probe system by including more than one probe head and using the elements of all of the probes to render an image, the lateral resolution of the image can be greatly improved. In order to render an image, the relative positions of all of the elements must be known precisely. Optionally, if the probe system has position and rotation adjustments, a display is provided to position all of the elements to be in the same plane of scan and to transmit or receive in the same plane of scan.

[0063] Figure 17 shows a probe system 1700 comprising three probes 1701, 1702, and 1703 working together as a multi-aperture transducer though not assembled in a single shell. This is not a standard embodiment of a multiple aperture transducer, but serves here to aid in describing arrays alignment. A multi-aperture transducer can comprise of any number of arrays 1710, 1720, 1730 (two or more), or even individual elements. For practical reasons, arrays in probes can easily be manufactured with a large number of elements and element spacing within a head can be well controlled.

If one can precisely position the end elements of each probe, it is possible to imply the positions of the other elements. Therefore, a fixture will be described which finds the positions of the elements. This apparatus could determine the exact location of independent elements either inside or outside of an array; however, because arrays are typically constructed in a linear format, the embodiment discussed here only identifies the end elements.

[0064] In Figure 17 these end elements are designated as element numbers 0 through 5, where 0 and 1 are the end elements of array 1710, 2 and 3 are the end elements of arrays 1720 and 4 and 5 are the end elements of array 1730. Any of the intermediate elements could be located in the same way as will be described.

[0065] A precision alignment stage assembly is shown in Figure 18A. The far left area of the assembly 1801 allows for the mechanical connection of a single probe, such as 1701 from Figure 17. The precision alignment stage assembly has three separate mechanisms 1801, 1802 and 1803 that control the position of the attached array in x, y and z axes. Several alignment stage assemblies can be used in concert so that multiple probe arrays can be manipulated independently. Figure 18B allows the operator to manipulate an array in any axis by using controls 1805, 1806, 1807, 1808, and bearing 1809. Precision screws 1804, 1805, 1806, 1807, and 1808 can be adjusted, and bearing 1809 can be rotated to affect one or more axes for the array during the alignment process.

[0066] Figure 25 shows the arrays 1710, 1720 and 1730 attached in line to precision alignment stages 2510, 2520 and 2530. With the arrays set in place, they can now transmit to common points of interest and compare their points of impact with the other arrays.

[0067] Figure 20 illustrates probes 1701, 1702 and 1703 from Figure 17 now attached to alignment stage assemblies above a tank or test block 2012. The tank can be filled with any liquid, fluid, gel, solid, or other medium 2014 that is desirable for manufacture and safety considerations, as long as the speed of sound for the fluid is known. The tank can include a mounting location for the alignment stage assemblies. In some embodiments, as shown in Figure 20, multiple alignment stage assemblies holding transducer elements can be mounted on the test block. From this position, it is possible to transmit ultrasonic pulses from the elements of any of the arrays to be received by ultrasonic sensor or hydrophones 2085 at the other end of the tank 2012.

[0068] Referring now to Figures 19a-19b, a multi-axis ultrasonic sensor or hydrophone 2085 may be used to detect the X, Y and Z positions of each element of a single array or multiple arrays under test. The multi-axis hydrophone 2085 can include a transverse hydrophone 2086, and right and left hydrophones 2087 and 2088. The common targets for the probes 1701, 1702 and 1703 to shoot at are elements 2091, 2092 and 2093 on the right hydrophone 2087. On the left hydrophone 2088, elements 2094, 2095, and 2096 are the targets.

[0069] The basic technique for aligning and calibrating a multiple aperture probe can now be addressed referring to Figures 19a, 19b and 20. The probe can be attached to a signal generator configured to excite any of the transducer elements to transmit ultrasonic pulses. An ultrasonic signal is transmitted which exhibits good autocorrelation properties (e.g., a long frequency sweep, or 'chirp' waveform, a short (wideband) pulse, a spread spectrum waveform, etc) from at least one element in arrays 1710, 1720 and 1730. The transmitted ultrasound signal can travel through the test block and be received by the receiving hydrophone transducer elements 2091, 2092, 2093, 2094, 2095, 2096 and the transverse hydrophone 2086. It is important to note that detection of the ultrasonic signal or pulse as received by the hydrophone arrays cannot be detected accurately enough by cross correlation with the signal impressed on the probe element because the probe element itself distorts the signal.

[0070] Two innovative techniques are used to obtain the needed accuracy in finding the relative time delays and hence the relative distances. The first technique is to use cross correlation between the signal received at one element of the hydrophone (for example 2091) and the signal received at another element of the same hydrophone (for example 2093). The correlation peak will yield the time difference and thus the distance difference.

[0071] The second technique is to interpolate between samples of the received waveforms to obtain better time resolution than simply the sampling interval. Perhaps the best way to accomplish both of these tasks is to take the Fourier transform of both signals, fill in zeros for the high frequency components of a much larger transform. Call these larger transforms FFT1 and FFT2. Then find the peak of the inverse transform of (FFT1 *(conjugate of FFT2)).

[0072] A third technique is necessary to convert differential distances to total distance. Consider the triangle bce in Figure 21a where the point b represents one of the elements for which we need to compute a position, and c and e are known reference points in the bottom of the water tank. It is desired to measure the lengths d_4 and d_0 by triangulation, but just knowing the difference between d_0 and d4 is not enough. By adding a transverse hydrophone (see 2086 In Figure 19a) in the bottom of the tank we have two triangles from which we can compute d_0 and d_4. Let e, d, and c be the locations of the hydrophones 2094, 2095 and 2096 or 2091, 2092 and 2093 of Figure 19a.

[0073] For the following analysis, the hydrophones 2094, 2095 and 2096 must be on the same line and on a parallel line to that formed by 2091, 2092 and 2093. The distance between 2094 and 2095 is designated d_1, and the distance between 2095 and 2096 is designated d_3. d_1 and d_3 must be known precisely as this becomes the reference "yardstick" for the other measurements. 2095 should be roughly centered between 2094 and 2096LN, but d_1 does not need to equal d_3. The same requirements apply to R0, RC, and RN.

[0074] Let d2 be the reference distance and define measured distances as:

$$d_{2m} = d_2 - d_2 = 0$$

$$d_{0m} = d_0 - d_2$$

$$d_{4m} = d_4 - d_2$$

[0075] From the law of cosines we have

$$d_4^2 = d_2^2 + d_3^2 - 2\, d_3\, d_2 \cos\alpha$$

$$d_0^2 = d_2^2 + d_1^2 - 2\, d_1\, d_2 \cos(\pi - \alpha) \qquad = d_2^2 + d_1^2 + 2\, d_1\, d_2 \cos\alpha$$

$$\cos\alpha = (d_4^2 - d_2^2 - d_3^2)/(-2\, d_3 d_2) \;=\; (d_0^2 - d_2^2 - d_1^2)/(2\, d_1 d_2)$$

$$d_4^2 - d_2^2 - d_3^2 = -(d_0^2 - d_2^2 - d_1^2) d_3/d_1$$

$$(d_{4m} + d_2)^2 - d_2^2 - d_3^2 + (d_{0m} + d_2)^2\, d_3/d_1 - d_2^2\, d_3/d_1 - d_1 d_3 = 0$$

[0076] Combining and cancelling terms this becomes

$$d_2 = (-\, d_{4m}^2 + d_3^2 - d_{om}^2\, d_3/d_1 + d_1 d_3) \,/\, (2\, d_{4m} + 2\, d_{0m}\, d_3/d_1)$$

Then $d_0 = d_{0m} + d_2$ and $d_4 = d_{4m} + d_2$.
Thus we have the full measurements from received differential times.

[0077] Two parallel "yardsticks" or right and left hydrophones are provided in the bottom of the tank in order to measure position along the z axis from Figure 1, and as is illustrated in Figure 23b. It will be the goal to position all of the probe elements from all three arrays 1701, 1702 and 1703 in a line midway between the two yardsticks using the various controls illustrated in Figure 18b.

[0078] Referring now to Figure 21b, consider the measurement of the position of any probe element such as M0 1206. First, consider using the right yardstick RO-RC-RN 2091, 2092, 2093. By transmitting a chirp signal from element M0 1206 and receiving it on hydrophones at R0, RC, and RN 2091, 2092 and 2093, one can calculate the differential times for transmission along the paths d_0, d_2, and d_4. Times can be converted to distances if the speed of ultrasound of the test block medium is known. If the test block medium is water, the speed of sound is approximately sos = 1.40238742 + 5.03821344 * TE/1000. - 5.80539349 *TE^2/100000. + 3.32000870 * TE^3/10000000. - 1.44537900 *TE^4/1000000000. + 2.99402365 *TE^5/1000000000000. (mm per microsecond) where TE is the temperature in degrees Celsius. Differential distances can be converted to total distances according to the derivation above.

[0079] Now from trigonometry, distance a = $((d_0^2 - d_4^2 + (d_1 + d_3)^2)/(2(d_1 + d_3))$ The position along the x' axis is d_1 -a. Assuming that the element is midway between the two yardsticks, then
the position along the y' axis is sqrt($(d_0 2 - a^2 - (zr/2)^2)$).

[0080] Initially considerable error may occur as a result of this assumption, but the measurement of z will allow for adjustment of the element or the entire probe assembly until this assumption is satisfied.

[0081] Again referring to Figure 21b, the same computations for x' and y' can be made using the left yardstick 2094, 2095 and 2095; and, the results can be averaged for increased accuracy. But the main reason for having two yardsticks is the ability to measure the z axis; the elements position in or out of the scan plane as illustrated in Figure 1. Then the array alignment apparatus can display it (see Figure 23a, 2300), and thus allow either manual (Figure 18b) or automatic (Figure 24) correction and alignment. The z variable is proportional to the time of arrival difference of the pulse as received at RC 2092 and LC 2095. The probe position should be adjusted until the time difference is close to zero. When this is done, all of the x and y measurements will be accurate and the relative positions of all of the elements will be known.

[0082] Finally a controller (such as a computer) can scan and find the maximum signal strength on the transverse hydrophone 2086 and record the angular displacement for the probe element.

[0083] To use the multiple aperture array alignment apparatus as a daily calibrator, multiple aperture ultrasound transducers will already be fully assembled, such as the embodiment illustrated in Figure 22. Therefore, all of these measurements will have to be referenced to axes on the probe assembly. In the multi-aperture transducer probe assembly 2200 shown in Figure 22, it would be reasonable to rotate and translate all measurements to a new coordinate system (x,y) centered on the center array. The appropriate coordinate system would be dependent on the ultrasound imaging system for which the probe assembly would be used. The multi-aperture probe can have a resident calibration memory or cal chip 2201 that can be programmed with calibration data received from the automated precision stage assembly, described below.

[0084] The transmit synchronization module 2202 is not related to calibration, but is necessary to identify the start of pulse when the probe is used as an add-on device with a host machine transmitting. The probe displacement sensor 2203 can be an accelerometer or gyroscope that senses the three dimensional movement of the probe. During calibration, the probe must be securely attached to the array alignment apparatus so that the probe is still.

[0085] Referring now to Figure 23a, a proprietary graphical user interface or GUI 2300, allows the elemental array data to be visualized in real-time allowing for correction of the x, y and z variation errors. The two wide vertical lines 2001 and 2003 represent the z positions of the yardsticks RO-RC-RN (2091, 2092, and 2093 from Figure 19a) and LO-LC-LN (2094, 2095, and 2096 from Figure 19a). The thinner vertical line 2302 is the z=0 line and the desired position of each of the elements of a probe system. The vertical position is the x coordinate.

[0086] Each small square, such as 2305, 2306, 2307, 2308, 2309, 2310 and 2011, is the position of a probe element in the x-z plane. In this example there are six small squares indicating the positions of the end elements of three probe heads. However, the positions of more or fewer elements could be displayed in this way. The thin horizontal lines 2312, 2313, 2314, 2315, 2316, 2317 and 2018 represent the directivity and angular spread of each element as detected on the multi-axis hydrophone. A useful angular spread measure is the number of hydrophone elements on the transverse hydrophone array which record signal strength greater or equal to half of the maximum strength.

[0087] Figure 23b depicts a probe element positioned correctly with the z position 2305 at or near z=0 and its directivity positioned over the centerline. In contrast, Figure 23c depicts a probe element with its z position 2305 offset toward the right hydrophone. The resulting display shows the small square, 2305, to the right of centerline, 2302. Note that in this case, the element position is in error, but the element directivity remains over the centerline as indicated on the display by the horizontal line 2312 remaining centered over centerline, 2302.

[0088] Finally, Figure 23d depicts a probe element correctly positioned with its z 2305 position at or near z=0, 2302. The directivity 2312, however, is misaligned in this case with an offset toward the left hydrophone as indicated by the horizontal line shifted to the left of centerline, 2302. In this case, the directivity needs to be corrected by adjusting the angulation to bring the directivity back over center. This could be accomplished, for example, by using controls 1805 and 1807 in Figure 18b. Thus with this display, element position and directivity can be monitored simultaneously and both brought into alignment.

[0089] Adjustments of the probe position and angulation with the precision alignment stage assembly or assemblies should continue until all of the small squares and all of the horizontal lines are aligned on the center vertical line as closely as practicable, ensuring in alignment in the z axis. As this is done, the x and y positions will be computed accurately and no separate iteration will be required for these.

[0090] In some manufacturing formats, arrays 2406 could be loaded into an automated precision stage assembly like the one in Figure 24. Here, arrays while still within their nose pieces can still be manipulated. In Figure 24, we see an automated precision stage assembly, 2406, fitted with precision stepper motors, 2403. Stepper motor controller, 2401, drives the transducer, 2405, under test in response to instructions from controller, 2402. The controller, 2401, evaluates data from the hydrophone assembly, 2404, and calculates transducer corrections. Test programs residing in the controller, 2402, provide transducer specific calibration data back to the transducer, 2405, under test incorporation in it's on board calibration chip, 2201. This automatically acquired element and array position data would be MAUI probe specific and would be used to optimize probe and system performance.

[0091] Using the precision stage assemblies with the array alignment system is only part of the value of the system. Figures 26a and 26b illustrate array alignment systems 2610 attached to the control unit 2620 of an ultrasound machine 2600. A cut away shows hydrophone assembly 2085 is located at the bottom of the fluid filled system 2610. In Figure 26a a MAUI general radiology probe 2630 is affixed to the system for testing. In Figure 26b, a MAUI cardiac probe 2640 is affixed to the system for calibration. The portability of this system, therefore allows for calibration of probes in the field multiple times per day. Additionally the MAUI system would alert the operator if service or maintenance was required.

[0092] To calibrate a probe, MAUI electronic apparatus can send a test pattern to the arrays in the probe to transmit to the hydrophone assembly 2085. When the positions of the probes and their directivities are reported as a result of the sequence, the positions of all of the elements can be downloaded to a file specific to that probe. Each file is stored in the probe calibration chip 2201. The calibration chip reports element positions in x, y and z axes to every MAUI electronic apparatus it connects to, and therefore can perform multiple aperture imaging without recalibrating before use with a different MAUI apparatus. The calibration chip memory can also be used to analyze probe performance and reliability.

[0093] In the special case in which all of the transmit and receive elements are aligned in the same plane or are manufactured so that there is no adjustment in z position, a simplified alignment fixture can be used. Instead of two parallel "yardsticks" of hydrophones, a single yardstick can be used. In this case the probe would be centered over the single yardstick using a plumb bob or a clamping device. The x and y measurements would then be made assuming z = 0 and zr=0. This is possible since accuracy in the value of z is much less critical in beamforming than is accuracy in the values of x and y. Thus adjusting z by the relatively crude methods of sighting with a plumb bob or clamping to a machined edge of the probe can be acceptable in spite of the high accuracy demands for measurement of x and y. Obviously, the cost of this simplified fixture would be much reduced resulting in a fixture which could be used in the field rather just in the probe assembly factory.

[0094] As for additional details pertinent to the present invention, materials and manufacturing techniques may be employed as within the level of those with skill in the relevant art. The same may hold true with respect to method-based aspects of the invention in terms of additional acts commonly or logically employed. Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Likewise, reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "and," "said," and "the" include plural referents unless the context clearly dictates otherwise. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation. Unless defined otherwise herein, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. The breadth of the present invention is not to be limited by the subject specification, but rather only by the plain meaning of the claim terms employed.

Claims

1. A system for measuring and aligning the positions of a plurality of transducer elements (0-5) in a multi-aperture ultrasound probe (1700, 1701, 1702, 1703), comprising:

    an alignment assembly (2406, 2510, 2520, 2530) configured to hold the plurality of transducer elements (0-5) of the multi-aperture ultrasound probe;
    a test block (2012);
    an ultrasonic sensor (2085) disposed in the test block configured to receive ultrasonic pulses through the test block from at least one of the plurality of transducer elements; and
    a controller configured to evaluate data from the ultrasonic sensor and provide transducer calibration data and wherein the controller runs an algorithm configured to compute the relative positions of the plurality of transducer elements based on the transducer calibration data.

2. The system of claim 1, wherein the test block (2012) comprises a tank filled with a liquid or a gelatinous material (2014) having a known speed of sound or the test block comprises a solid block having a known speed of sound.

3. The system of claim 1 further comprising a signal generator that is configured to: (i) excite at least one of the plurality of transducer elements (0-5) to transmit ultrasonic pulses, (ii) excite the plurality of transducer elements with a short (wideband) pulse, (iii) excite the plurality of transducer elements with a spread spectrum waveform, or (iv) excite at least one of the plurality of transducer elements with a chirp waveform.

4. The system of claim 1, wherein the alignment assembly (2510, 2520, 2530) comprises an automated alignment assembly configured to automatically align the plurality of transducer elements (0-5) based on the transducer calibration data from the controller.

5. The system of claim 4, wherein the alignment assembly (2406) comprises at least one stepper motor (2403) and a stepper motor controller (2401) for driving the at least one stepper motor to align the transducer elements.

6. The system of claim 1 wherein the alignment assembly (2510, 2520, 2530) comprises a manual alignment assembly that includes manual controls configured to manipulate the plurality of transducer elements (0-5) in the x, y, and z axes.

7. The system of claim 1, wherein the controller runs algorithms configured to compute complete transit times from at least one of the plurality of transducer elements (0-5) to a plurality of receiving transducer elements (2091-2096) disposed on the ultrasonic sensor (2085).

8. The system of claim 1, wherein the alignment assembly (2510, 2520, 2530) is configured to hold a probe (1700, 1701, 1702, 1703) containing the plurality of transducer elements (0-5).

9. The system of claim 1, wherein the ultrasonic sensor (2085) includes a plurality of receiving transducer elements (2091-2096).

10. The system of claim 1, wherein the controller is configured to digitize and store the received ultrasonic pulses.

11. A method for measuring and aligning the positions of transducer elements (0-5) in a multi-aperture ultrasound probe (1700, 1701, 1702, 1703), comprising:

mounting a plurality of transducer elements (0-5) of the multi-aperture ultrasound probe in an alignment assembly (2510, 2520, 2530);
transmitting ultrasonic pulses through a test block (2012) from at least one of the plurality of transducer elements;
receiving the ultrasonic pulses with an ultrasonic sensor (2085) disposed in the test block;
evaluating the received ultrasonic pulses from the ultrasonic sensor with a controller to provide transducer calibration data; and
running an algorithm with the controller that is configured to compute the relative positions of the plurality of transducer elements based on the transducer calibration data.

12. The method of claim 11 further comprising automatically or manually aligning the plurality of transducer elements (0-5) based on the transducer calibration data.

Patentansprüche

1. System zum Messen und Ausrichten der Positionen mehrerer Wandlerelemente (0-5) in einer Ultraschall-Sonde (1700, 1701, 1702, 1703) mit mehreren Öffnungen, umfassend:

eine Ausrichtungsanordnung (2406, 2510, 2520, 2530), die konfiguriert ist, um die mehreren Wandlerelemente (0-5) der Ultraschall-Sonde mit mehreren Öffnungen zu halten;
einen Testblock (2012);
einen Ultraschallsensor (2085), der in dem Testblock angeordnet und so konfiguriert ist, dass er Ultraschallimpulse von mindestens einem der mehreren Wandlerelemente durch den Testblock empfängt; und
eine Steuerung, die konfiguriert ist, um Daten von dem Ultraschallsensor auszuwerten und Wandlerkalibrierungsdaten bereitzustellen, und wobei die Steuerung einen Algorithmus ausführt, der konfiguriert ist, um die relativen Positionen der mehreren Wandlerelemente auf Basis der Wandlerkalibrierungsdaten zu berechnen.

2. System nach Anspruch 1, wobei der Testblock (2012) einen Tank umfasst, der mit einem flüssigen oder gelartigen Material (2014) mit einer bekannten Schallgeschwindigkeit gefüllt ist, oder wobei der Testblock einen festen Block mit einer bekannten Schallgeschwindigkeit umfasst.

3. System nach Anspruch 1, das weiterhin einen Signalgenerator umfasst, der konfiguriert ist, um: (i) mindestens eines der mehreren Wandlerelemente (0-5) anzuregen, um Ultraschallimpulse zu übertragen, (ii) die mehreren Wandlerelemente mit einem kurzen (Breitband-)Impuls anzuregen, (iii) die mehreren Wandlerelemente mit einer Frequenzspreizungs-Wellenform anzuregen oder (iv) mindestens eines der mehreren Wandlerelemente mit einer Chirp-Wellenform anzuregen.

4. System nach Anspruch 1, wobei die Ausrichtungsanordnung (2510, 2520, 2530) eine automatisierte Ausrichtungsanordnung umfasst, die konfiguriert ist, um die mehreren Wandlerelemente (0-5) auf Basis der Wandlerkalibrierungsdaten der Steuerung automatisch auszurichten.

5. System nach Anspruch 4, wobei die Ausrichtungsanordnung (2406) mindestens einen Schrittmotor (2403) und eine Schrittmotorsteuerung (2401) zum Antreiben des mindestens einen Schrittmotors zum Ausrichten der Wandlerele-

mente umfasst.

6. System nach Anspruch 1, wobei die Ausrichtungsanordnung (2510, 2520, 2530) eine manuelle Ausrichtungsanordnung umfasst, die manuelle Steuerungen beinhaltet, die konfiguriert sind, um die mehreren Wandlerelemente (0-5) in den x-, y- und z-Achsen zu manipulieren.

7. System nach Anspruch 1, wobei die Steuerung Algorithmen ausführt, die konfiguriert sind, um vollständige Laufzeiten von mindestens einem der mehreren Wandlerelemente (0-5) zu mehreren empfangenden Wandlerelementen (2091-2096) zu berechnen, die auf dem Ultraschallsensor (2085) angeordnet sind.

8. System nach Anspruch 1, wobei die Ausrichtungsanordnung (2510, 2520, 2530) konfiguriert ist, um eine Sonde (1700, 1701, 1702, 1703) zu halten, die die mehreren Wandlerelemente (0-5) enthält.

9. System nach Anspruch 1, wobei der Ultraschallsensor (2085) mehrere empfangende Wandlerelemente (2091-2096) beinhaltet.

10. System nach Anspruch 1, wobei die Steuerung konfiguriert ist, um die empfangenen Ultraschallimpulse zu digitalisieren und zu speichern.

11. Verfahren zum Messen und Ausrichten der Positionen von Wandlerelementen (0-5) in einer Ultraschall-Sonde (1700, 1701, 1702, 1703) mit mehreren Öffnungen, umfassend:

Anbringen mehrerer Wandlerelemente (0-5) der Ultraschall-Sonde mit mehreren Öffnungen in eine Ausrichtungsanordnung (2510, 2520, 2530);
Übertragen von Ultraschallimpulsen durch einen Testblock (2012) von mindestens einem der mehreren Wandlerelemente;
Empfangen der Ultraschallimpulse mit einem Ultraschallsensor (2085), der in dem Testblock angeordnet ist;
Auswerten der von dem Ultraschallsensor empfangenen Ultraschallimpulse mit einer Steuerung, um Wandlerkalibrierungsdaten bereitzustellen; und
Ausführen eines Algorithmus mit der Steuerung, die konfiguriert ist, um die relativen Positionen der mehreren Wandlerelemente auf Basis der Wandlerkalibrierungsdaten zu berechnen.

12. Verfahren nach Anspruch 11, das weiterhin ein automatisches oder manuelles Ausrichten der mehreren Wandlerelemente (0-5) auf Basis der Wandlerkalibrierungsdaten umfasst.

Revendications

1. Système de mesure et d'alignement des positions d'une pluralité d'éléments transducteurs (0-5) dans une sonde à ultrasons à ouvertures multiples (1700, 1701, 1702, 1703), comprenant :

un ensemble d'alignement (2406, 2510, 2520, 2530) configuré pour supporter la pluralité d'éléments transducteurs (0-5) de la sonde à ultrasons à ouvertures multiples ;
un bloc de test (2012) ;
un capteur à ultrasons (2085) disposé dans le bloc de test configuré pour recevoir des impulsions ultrasonores à travers le bloc de test provenant d'au moins un élément transducteur de la pluralité d'éléments transducteurs ; et
un dispositif de commande configuré pour évaluer des données provenant du capteur à ultrasons et fournir des données d'étalonnage de transducteur et dans lequel le dispositif de commande exécute un algorithme configuré pour calculer les positions relatives de la pluralité d'éléments transducteurs sur la base des données d'étalonnage de transducteur.

2. Système selon la revendication 1, dans lequel le bloc de test (2012) comprend un réservoir rempli d'un liquide ou d'une matière gélatineuse (2014) ayant une vitesse de son connue ou le bloc de test comprend un bloc solide ayant une vitesse de son connue.

3. Système selon la revendication 1 comprenant en outre un générateur de signal qui est configuré pour : (i) exciter au moins un élément transducteur de la pluralité d'éléments transducteurs (0-5) pour transmettre des impulsions ultrasonores, (ii) exciter la pluralité d'éléments transducteurs à l'aide d'une impulsion courte (large bande), (iii) exciter

la pluralité d'éléments transducteurs à l'aide d'une forme d'onde à spectre étalé, ou (iv) exciter au moins un élément transducteur parmi la pluralité d'éléments transducteurs à l'aide d'une forme d'onde chirp.

4. Système selon la revendication 1, dans lequel l'ensemble d'alignement (2510, 2520, 2530) comprend un ensemble d'alignement automatisé configuré pour aligner automatiquement la pluralité d'éléments transducteurs (0-5) sur la base des données d'étalonnage de transducteur à partir du dispositif de commande.

5. Système selon la revendication 4, dans lequel l'ensemble d'alignement (2406) comprend au moins un moteur pas à pas (2403) et une commande de moteur pas à pas (2401) pour amener l'au moins un moteur pas à pas à aligner les éléments transducteurs.

6. Système selon la revendication 1, dans lequel l'ensemble d'alignement (2510, 2520, 2530) comprend un ensemble d'alignement manuel qui comporte des commandes manuelles configurées pour manipuler la pluralité d'éléments transducteurs (0-5) dans les axes x, y, et z.

7. Système selon la revendication 1, dans lequel le dispositif de commande exécute des algorithmes configurés pour calculer des temps de transit complets d'au moins l'un de la pluralité d'éléments transducteurs (0-5) à une pluralité d'éléments transducteurs récepteurs (2091-2096) disposés sur le capteur à ultrasons (2085).

8. Système selon la revendication 1, dans lequel l'ensemble d'alignement (2510, 2520, 2530) est configuré pour supporter une sonde (1700, 1701, 1702, 1703) contenant la pluralité d'éléments transducteurs (0-5).

9. Système selon la revendication 1, dans lequel le capteur à ultrasons (2085) comporte une pluralité d'éléments transducteurs récepteurs (2091-2096).

10. Système selon la revendication 1, dans lequel le dispositif de commande est configuré pour numériser et stocker les impulsions ultrasonores reçues.

11. Système de mesure et d'alignement des positions d'une pluralité d'éléments transducteurs (0-5) dans une sonde à ultrasons à ouvertures multiples (1700, 1701, 1702, 1703), comprenant :

le montage d'une pluralité d'éléments transducteurs (0-5) de la sonde à ultrasons à ouvertures multiples dans un ensemble d'alignement (2510, 2520, 2530) ;
la transmission d'impulsions ultrasonores à travers un bloc de test (2012) à partir d'au moins l'un de la pluralité d'éléments transducteurs ;
la réception des impulsions ultrasonores avec un capteur à ultrasons (2085) disposé dans le bloc de test ;
l'évaluation des impulsions ultrasonores reçues du capteur à ultrasons à l'aide d'un dispositif de commande pour fournir des données d'étalonnage du transducteur ; et
l'exécution d'un algorithme avec le dispositif de commande qui est configuré pour calculer les positions relatives de la pluralité d'éléments transducteurs sur la base des données d'étalonnage du transducteur.

12. Procédé selon la revendication 11 comprenant en outre l'alignement automatique ou manuel de la pluralité d'éléments transducteurs (0-5) sur la base des données d'étalonnage du transducteur.

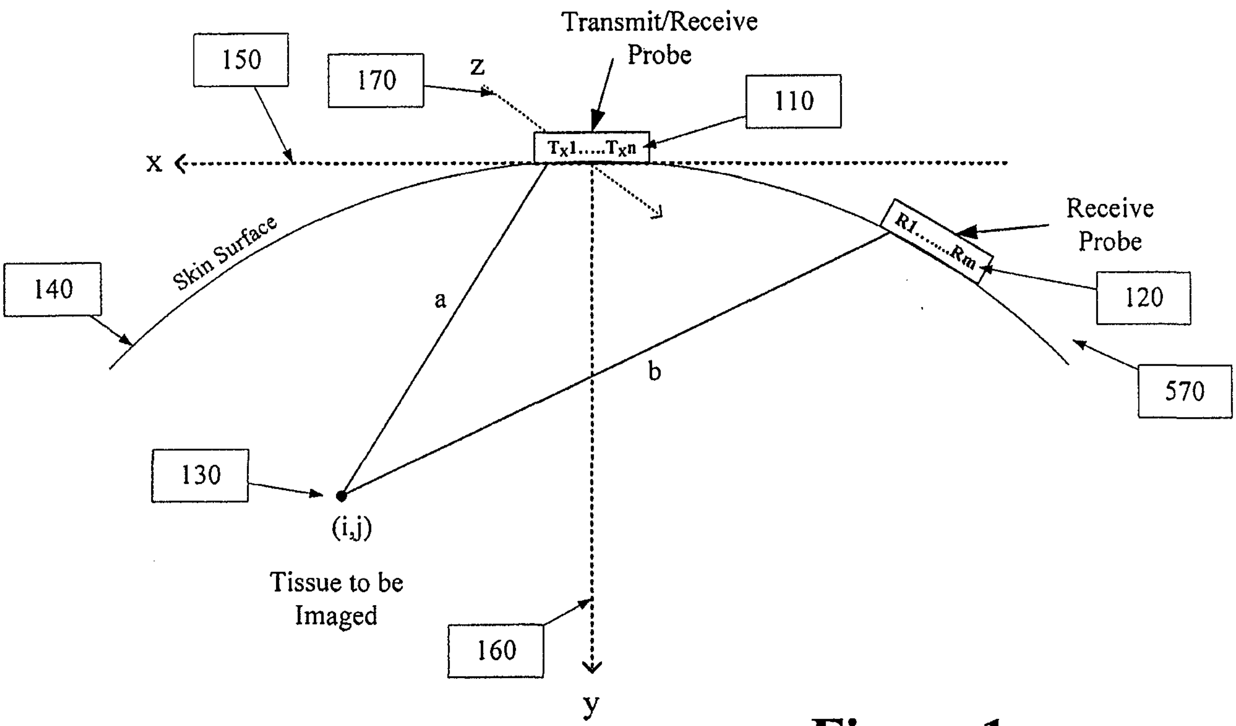

Transmit/Receive
Probe
150
170
Z
110
X
T_x1.....T_xn
Receive
Probe
Skin Surface
R1......Rm
140
a
120
b
570
130
(i,j)
Tissue to be
Imaged
160
y

Figure 1

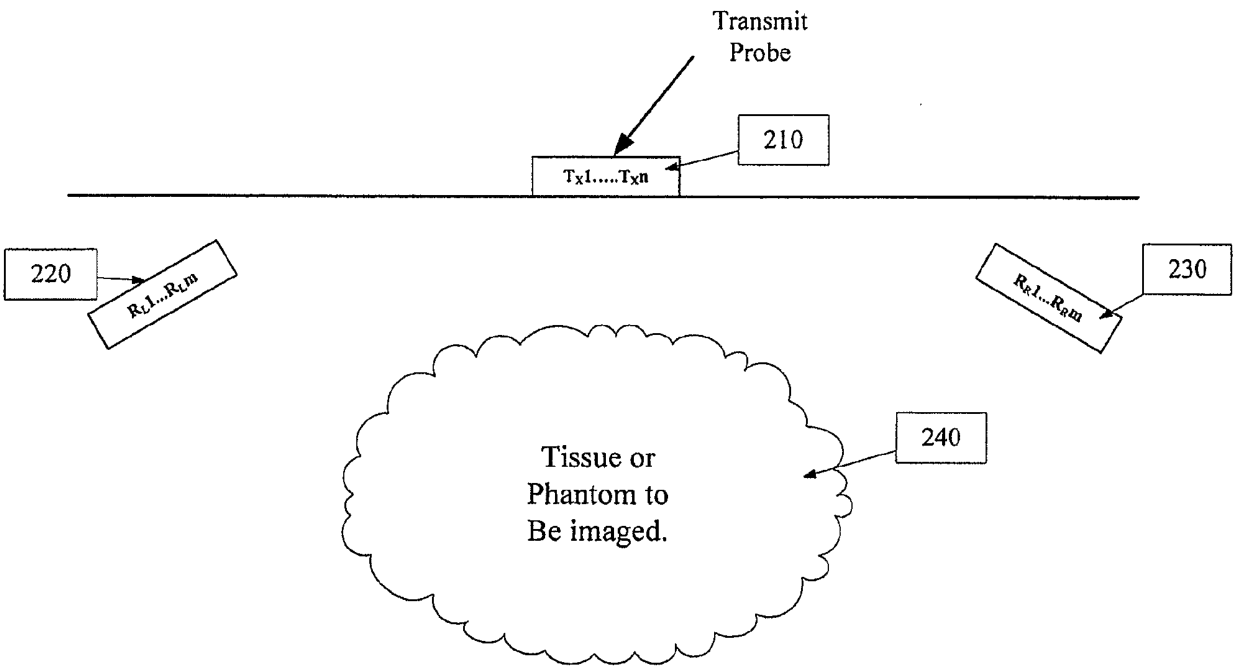

Transmit
Probe
210
Tx1.....Txn
220
RL1...RLm
230
RR1...RRm
240
Tissue or
Phantom to
Be imaged.

Figure 2

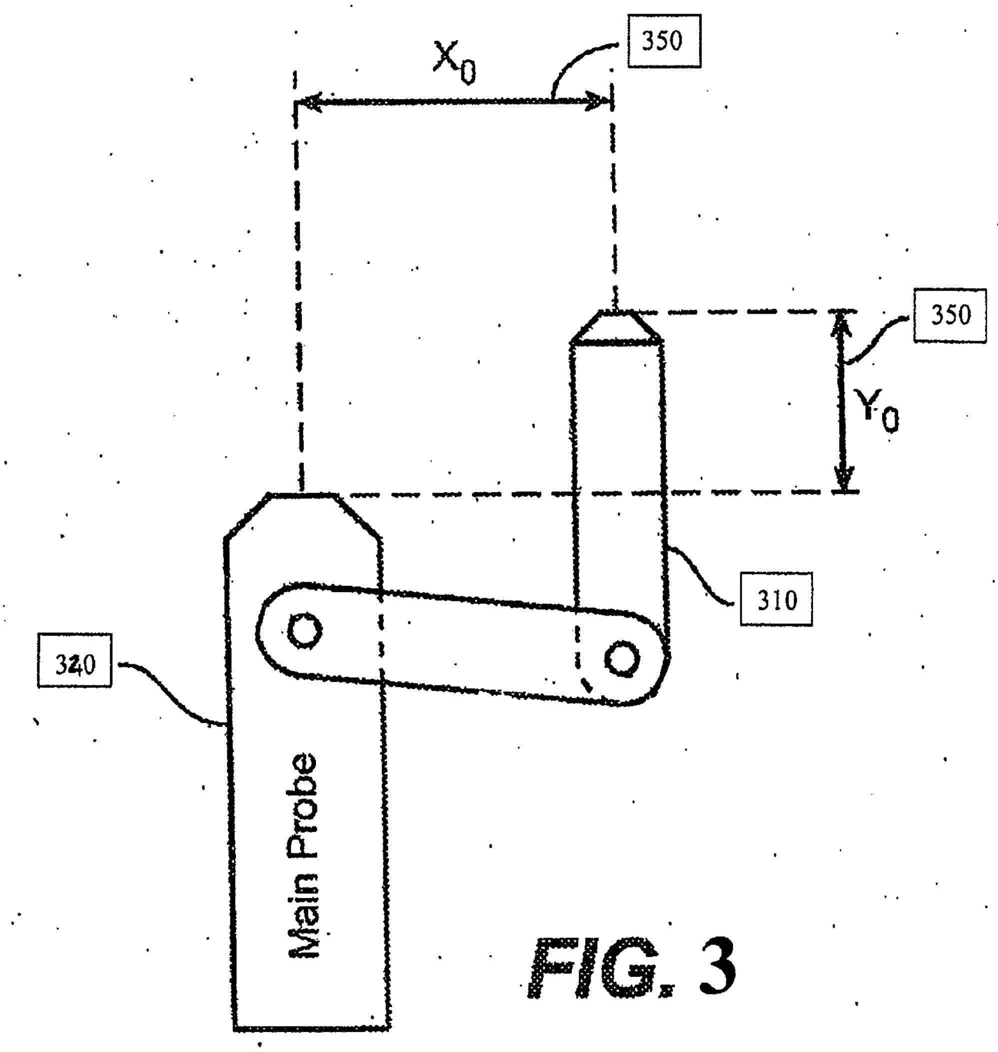
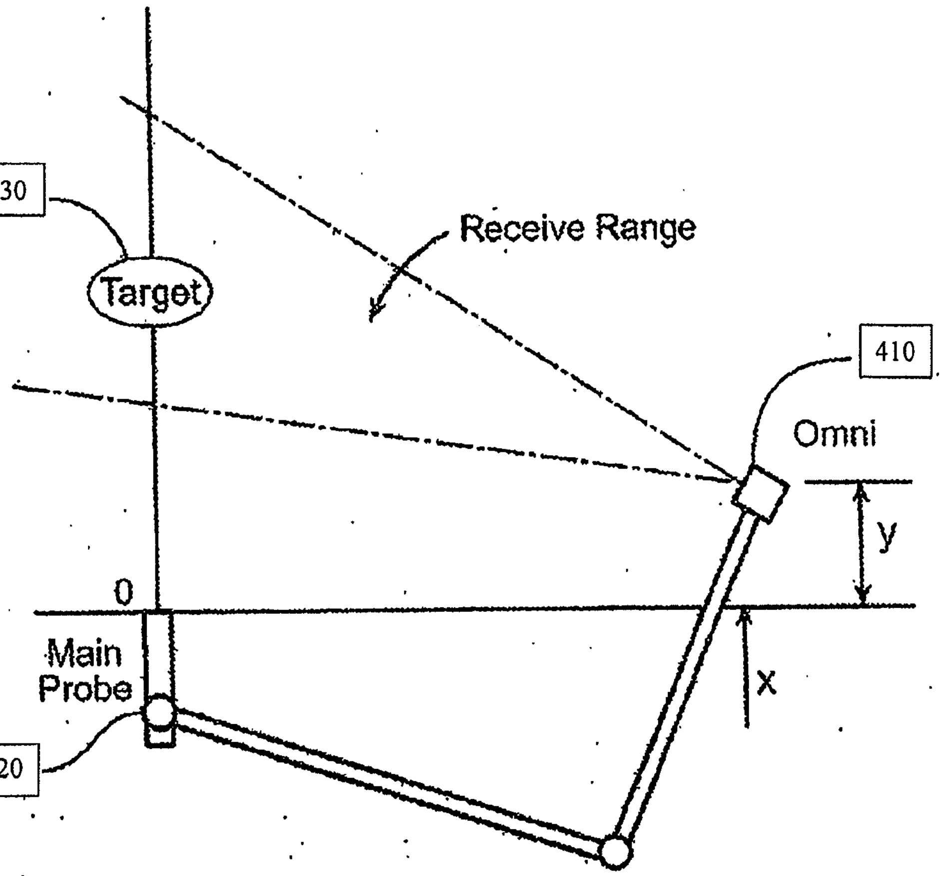


FIG. 3

FIG. 4



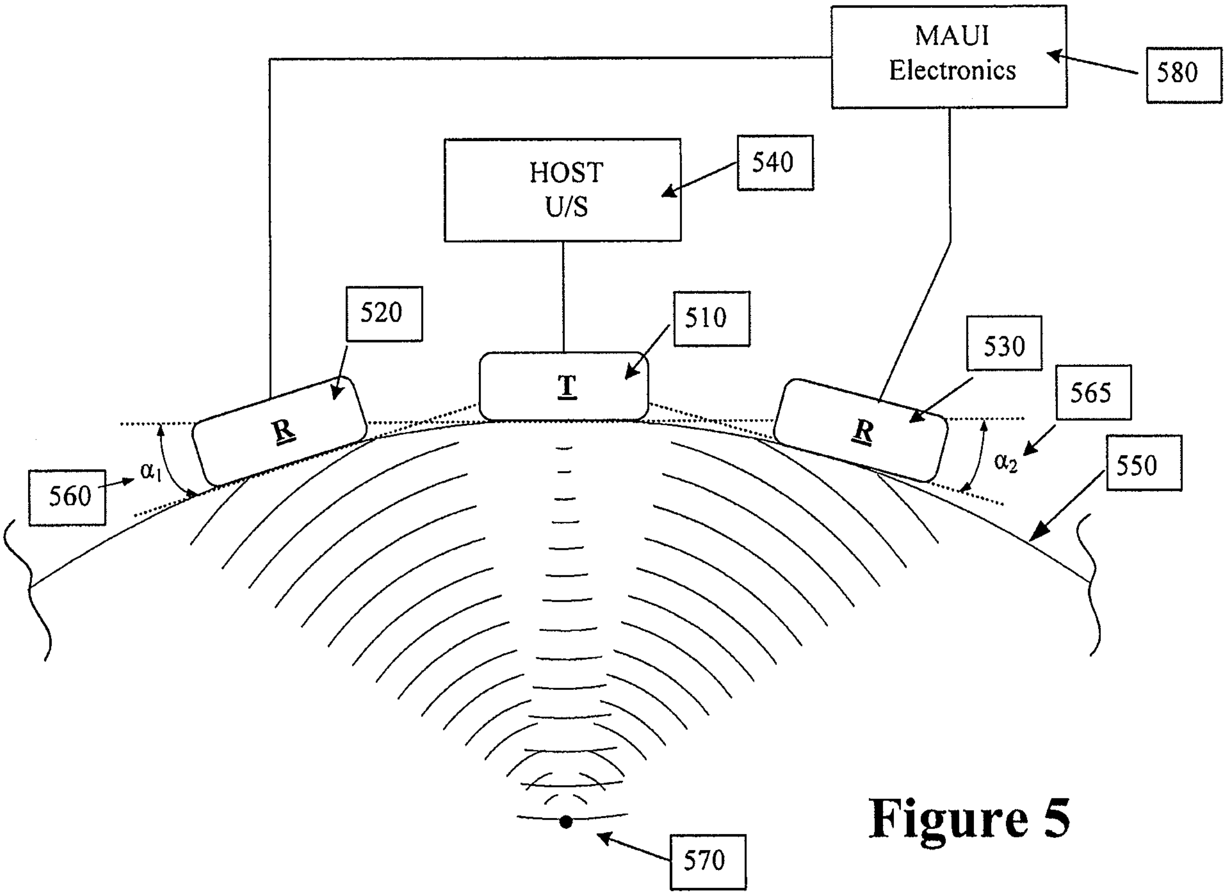


Figure 5

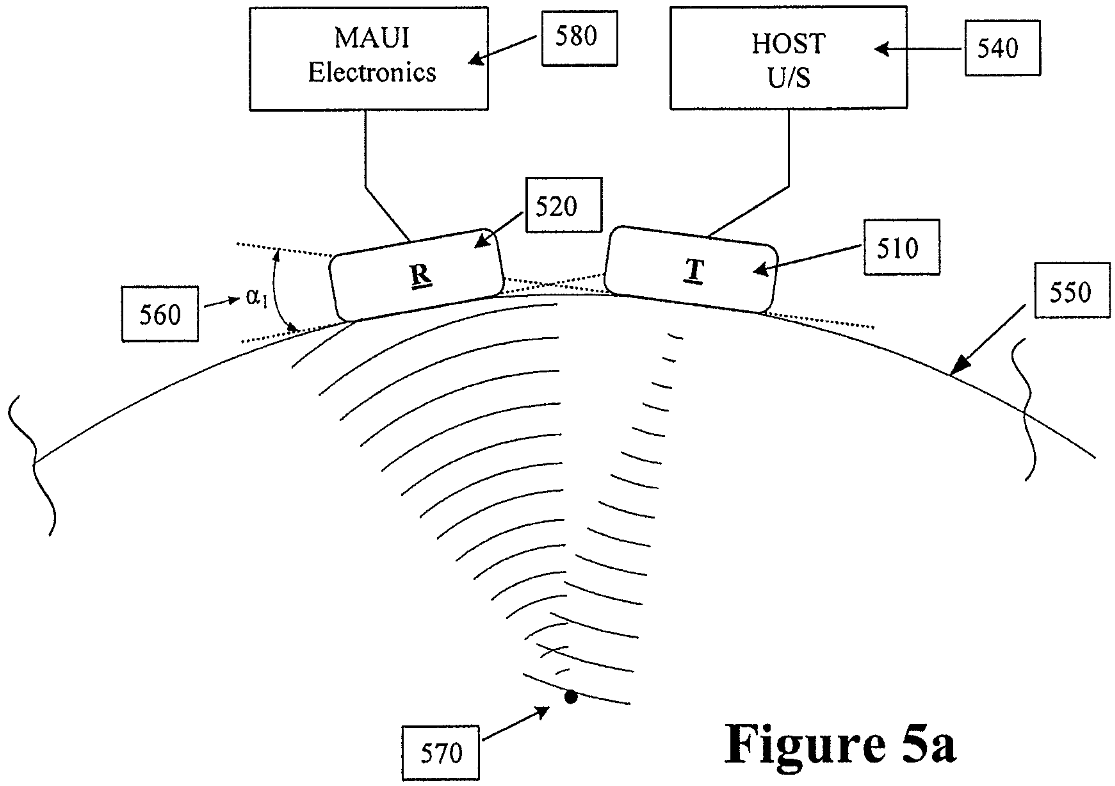


Figure 5a

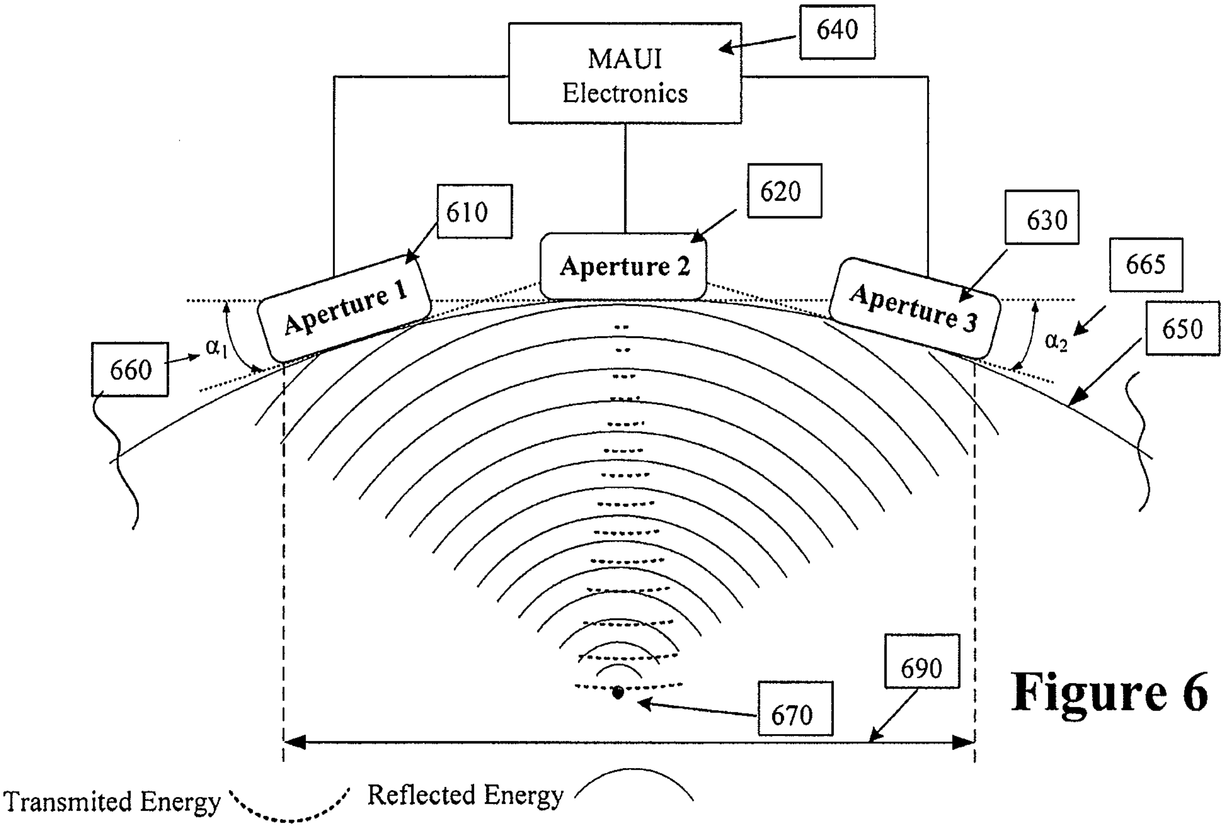


Figure 6

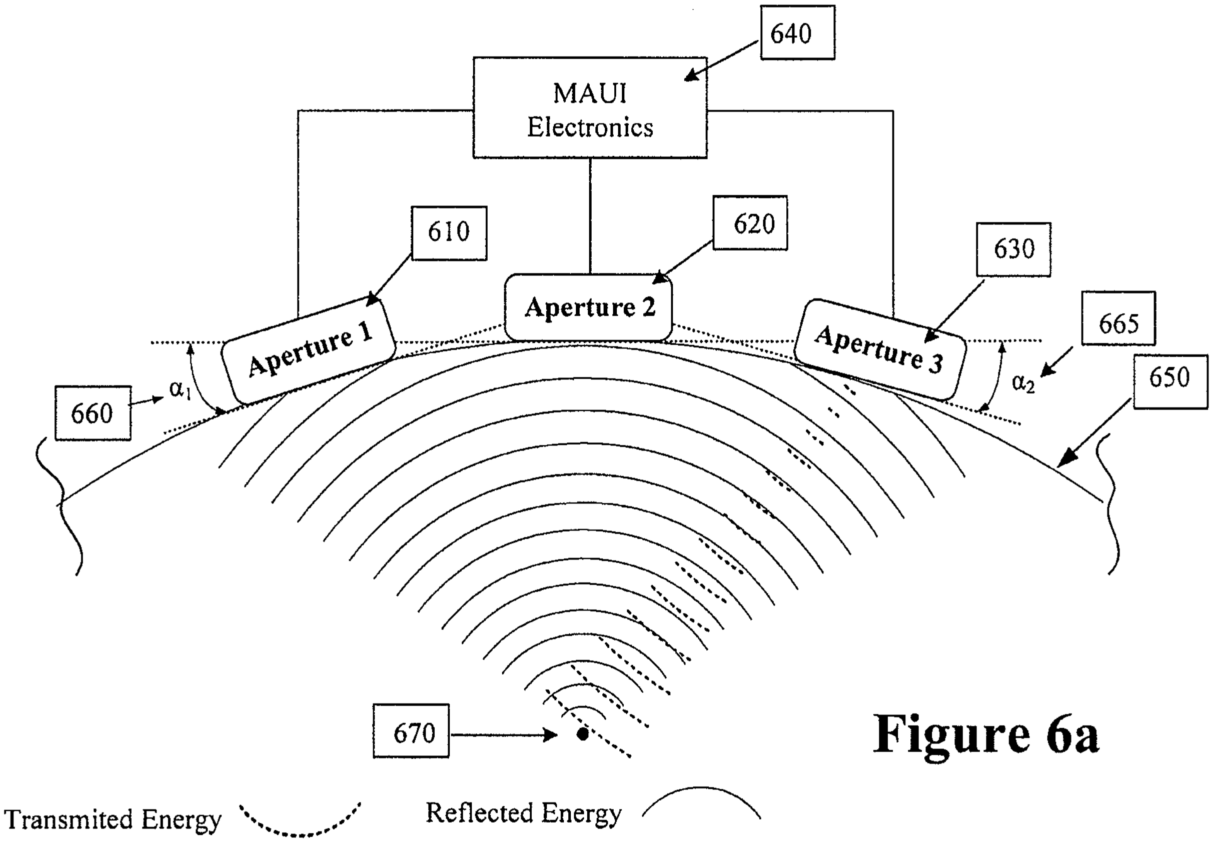


Figure 6a

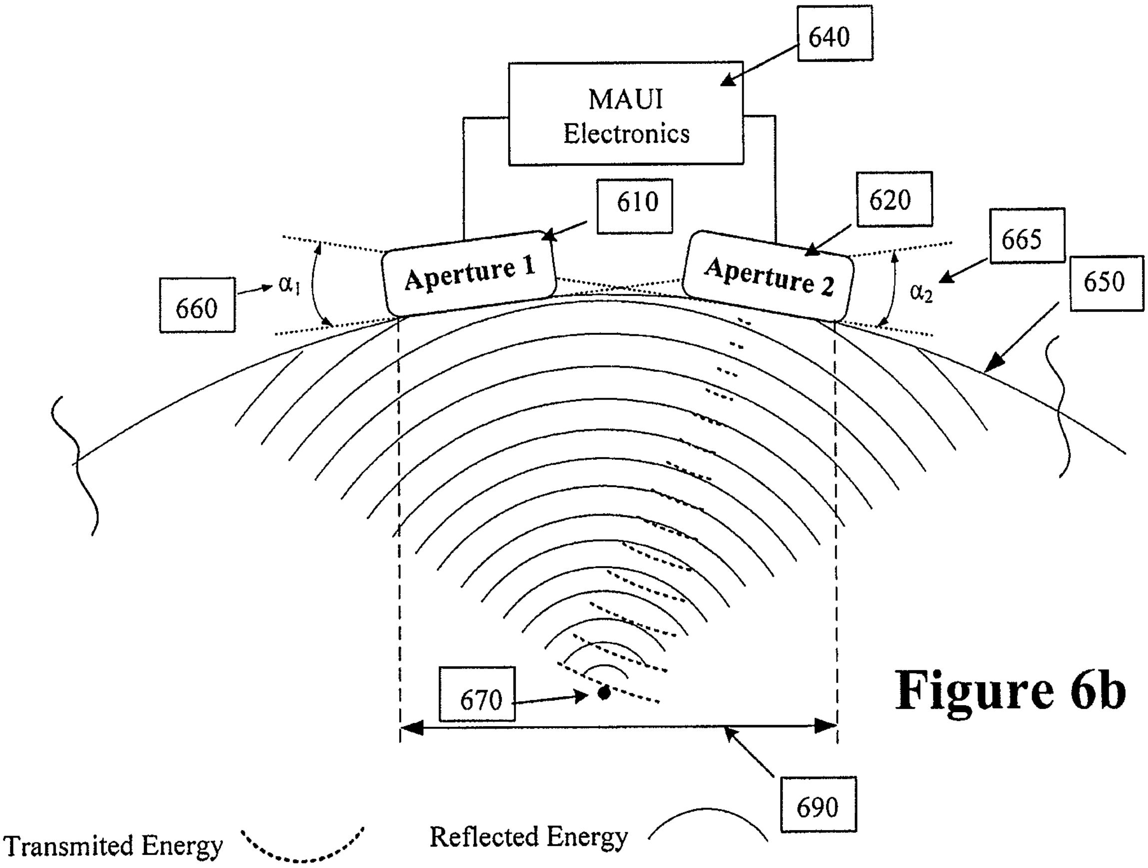


Figure 6b

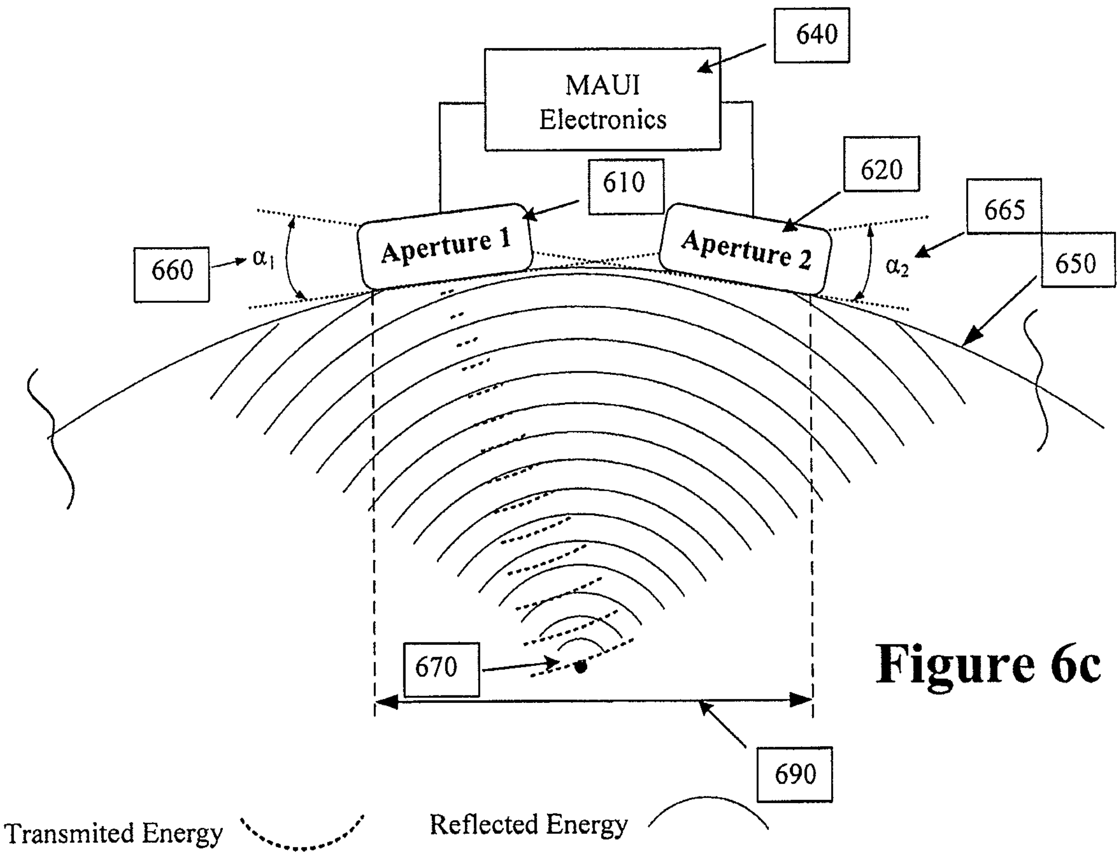


Figure 6c

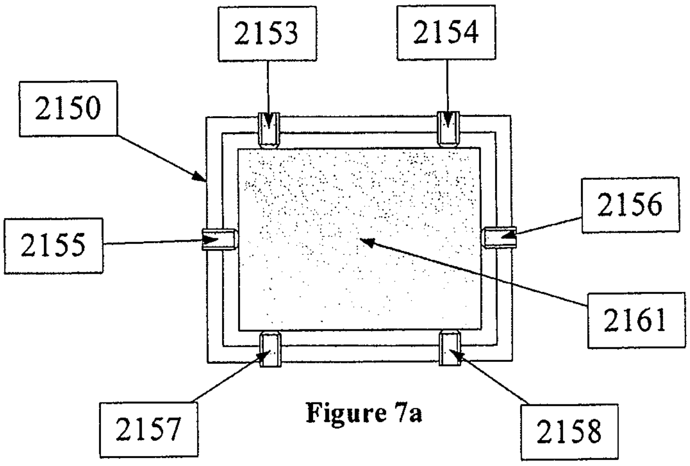


Figure 7a

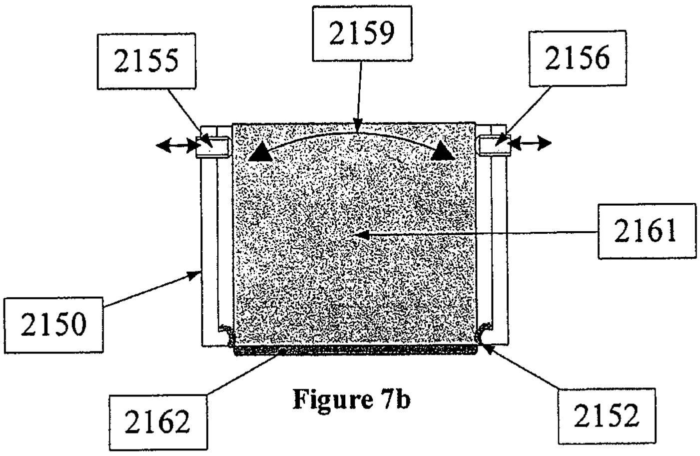


Figure 7b

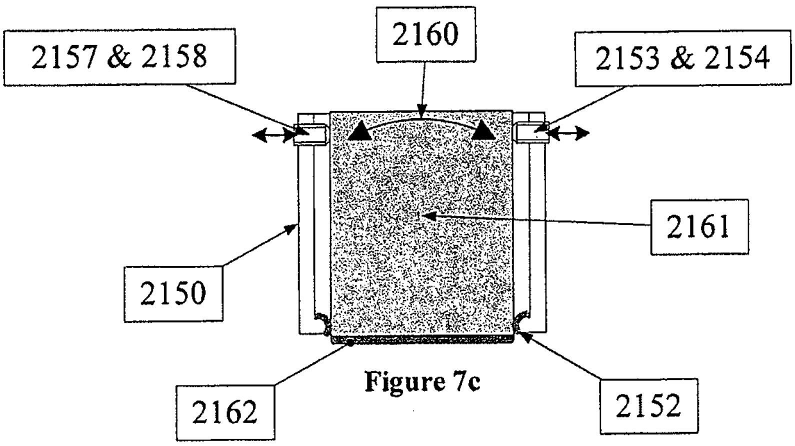


Figure 7c

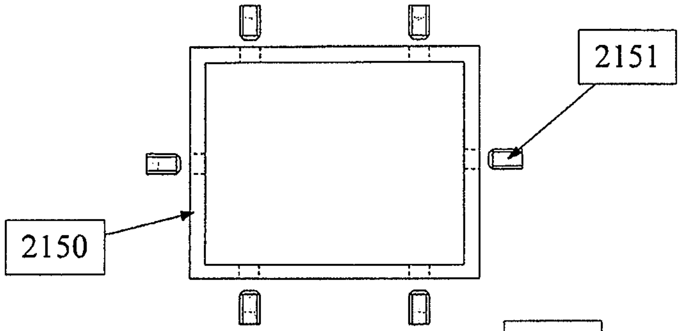


Figure 8a

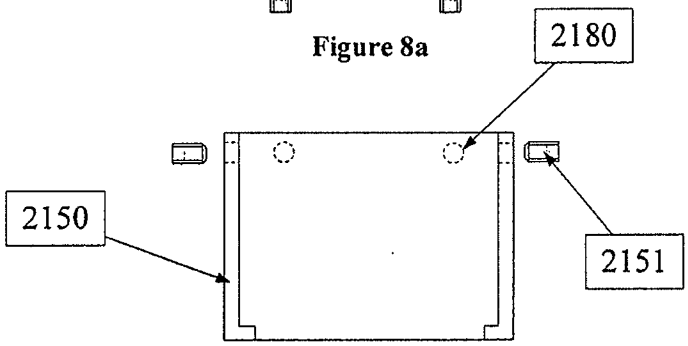


Figure 8b

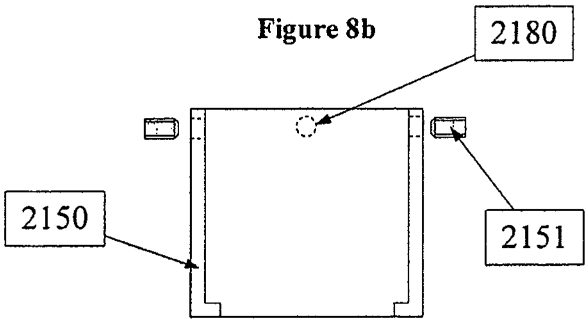


Figure 8c

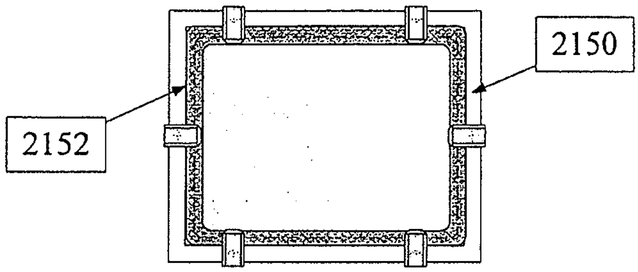


Figure 9a

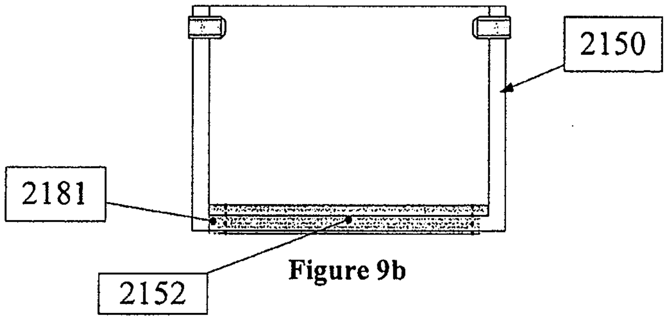


Figure 9b

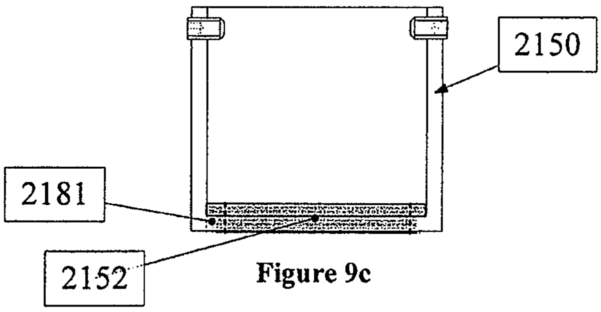


Figure 9c

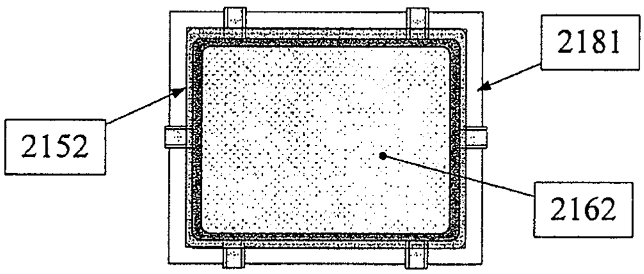


Figure 9d

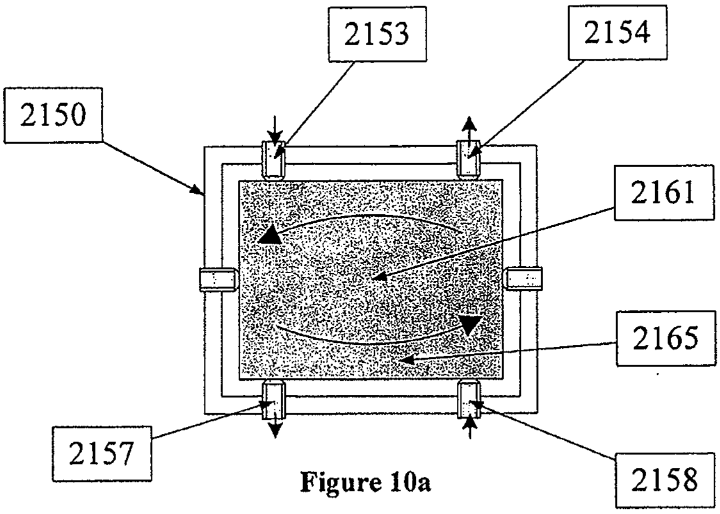


Figure 10a

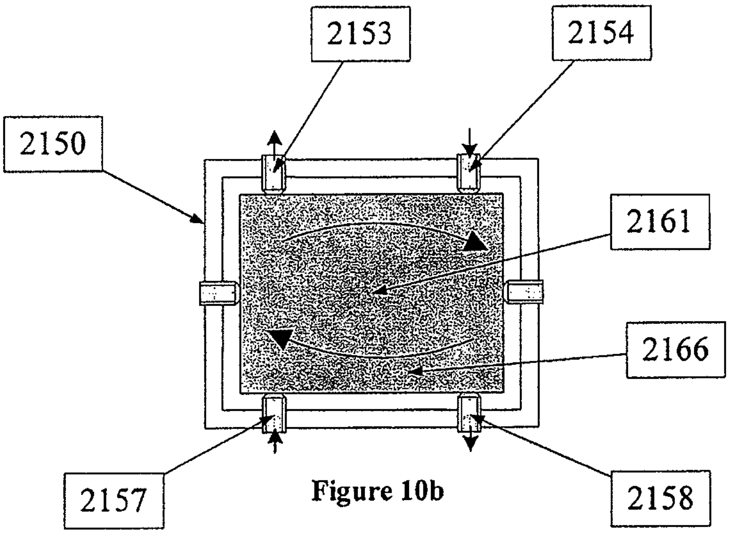
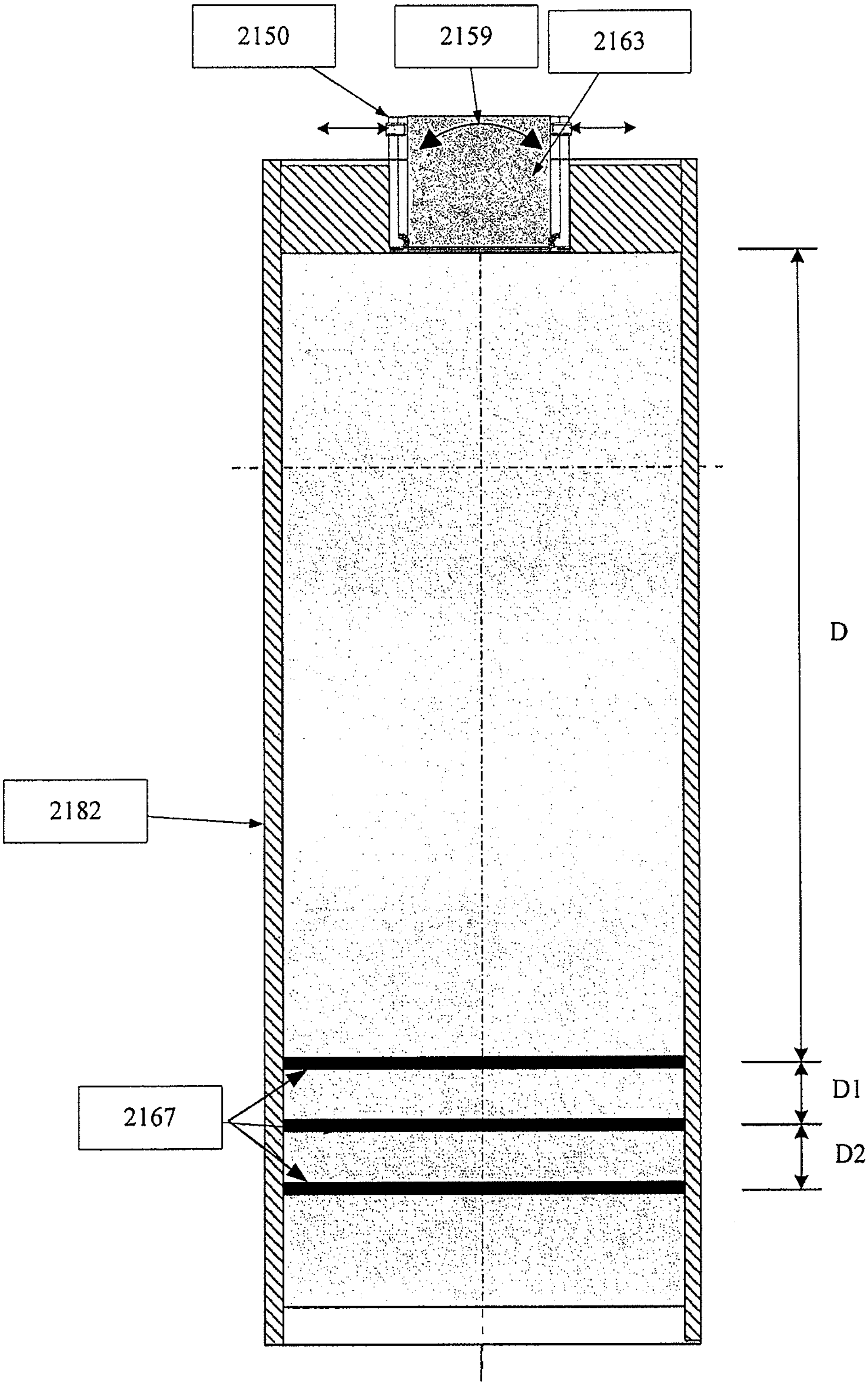
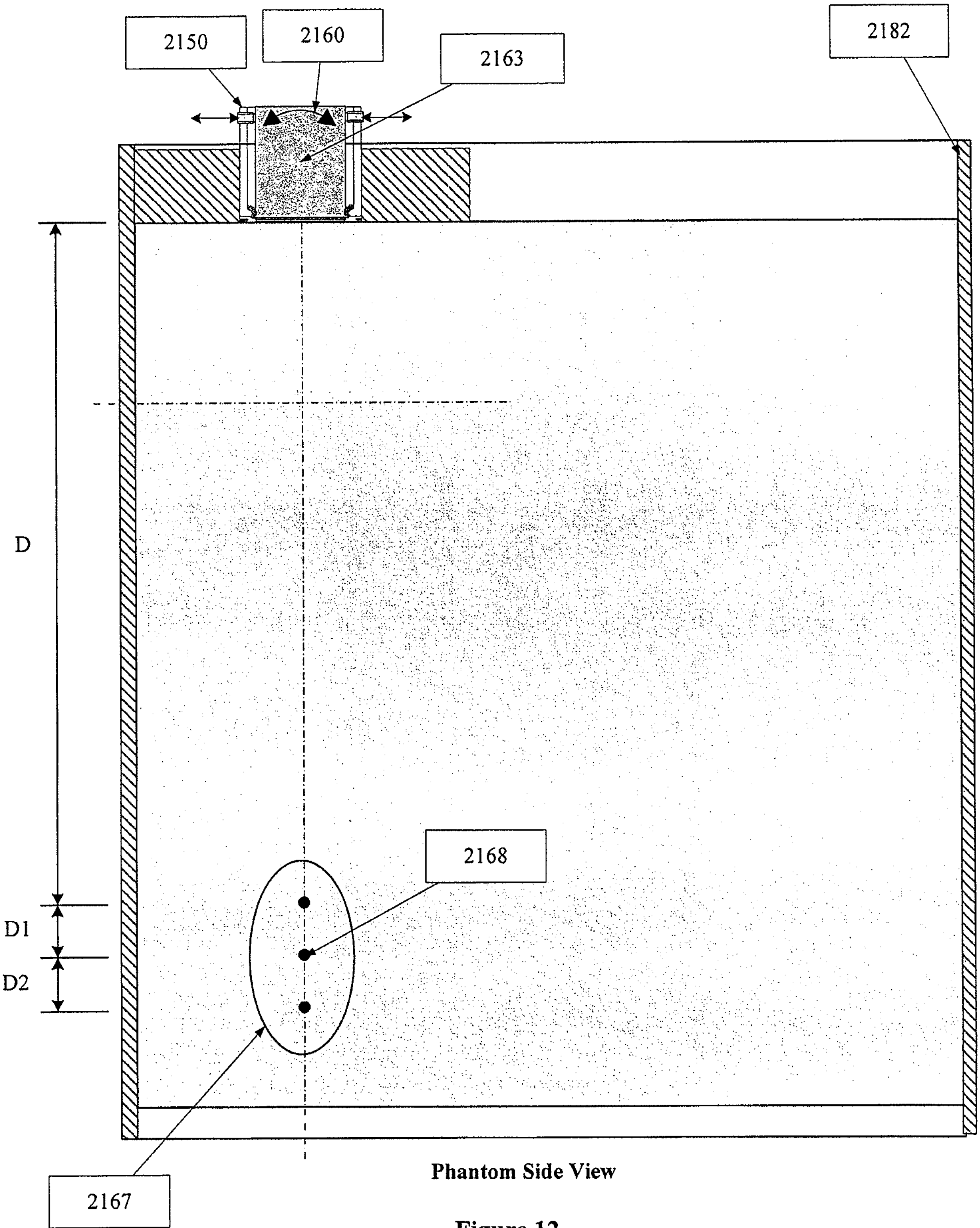


Figure 10b



Phantom End View

Figure 11



Phantom Side View

Figure 12

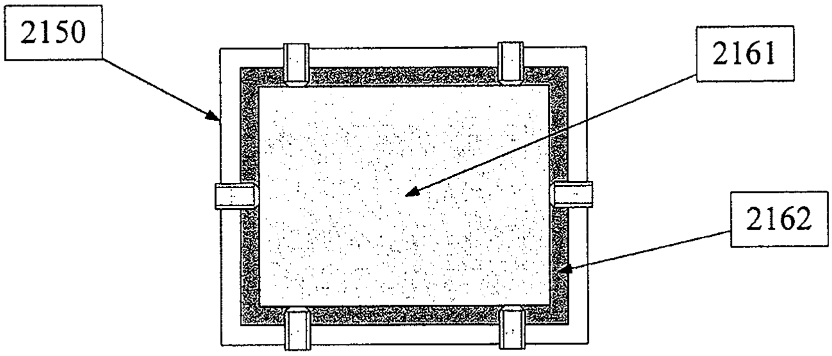


Figure 13a

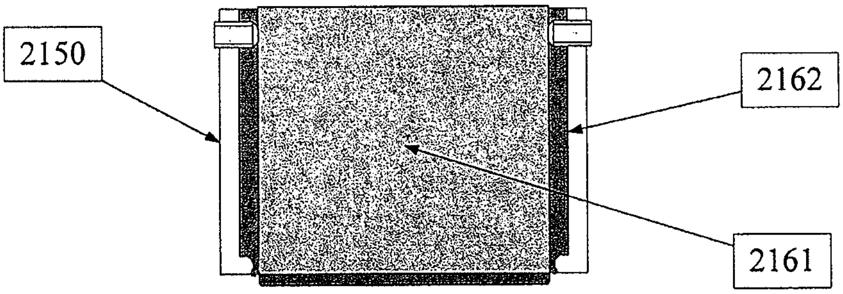


Figure 13b

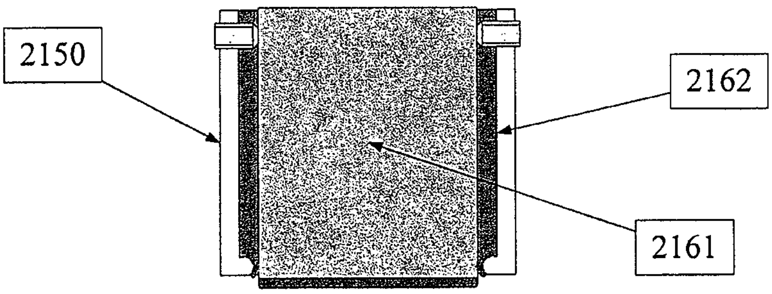


Figure 13c

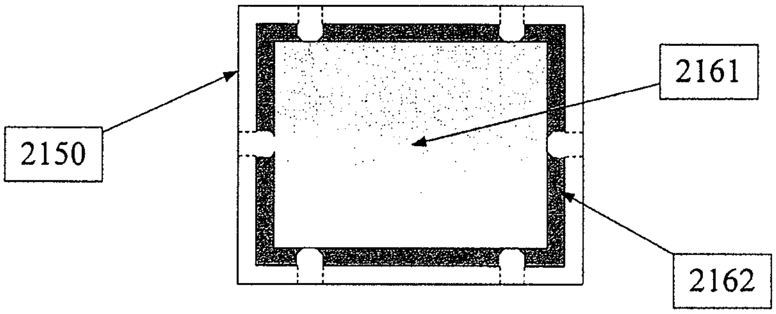


Figure 14a

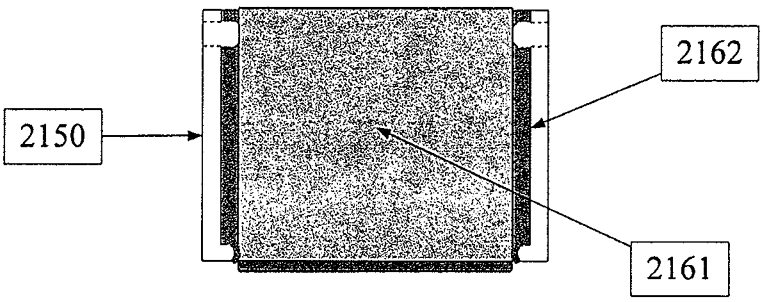


Figure 14b

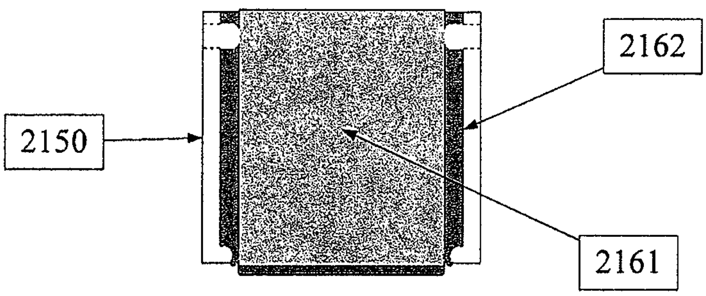


Figure 14c

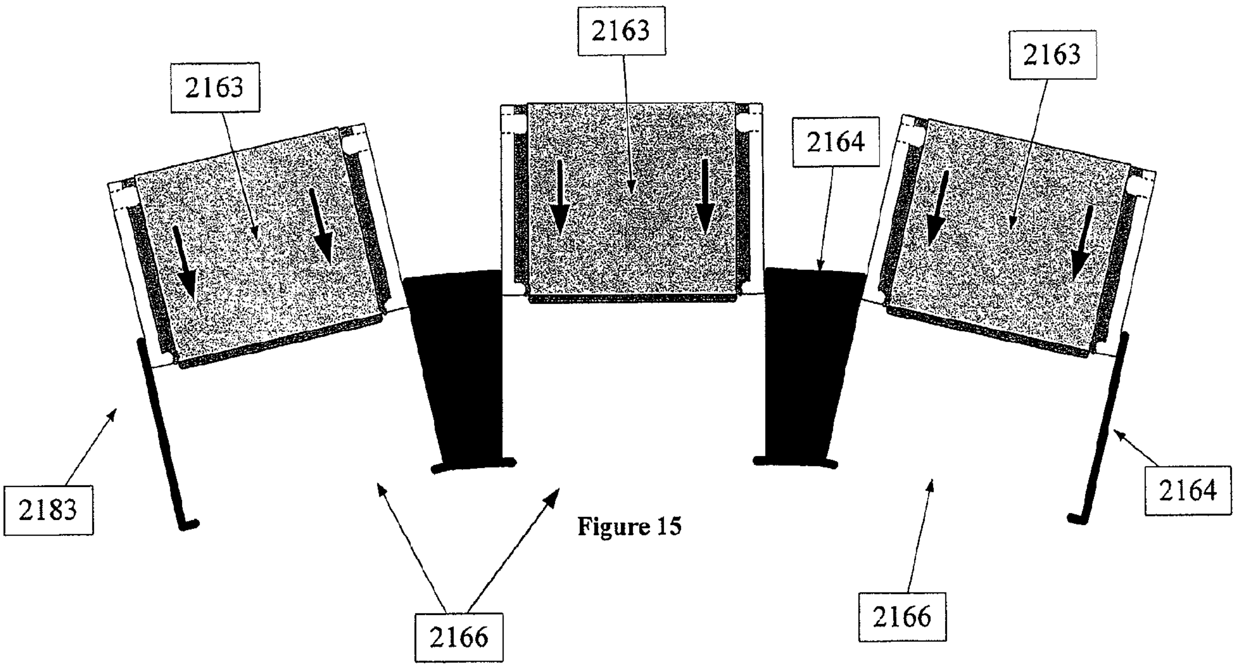


Figure 15

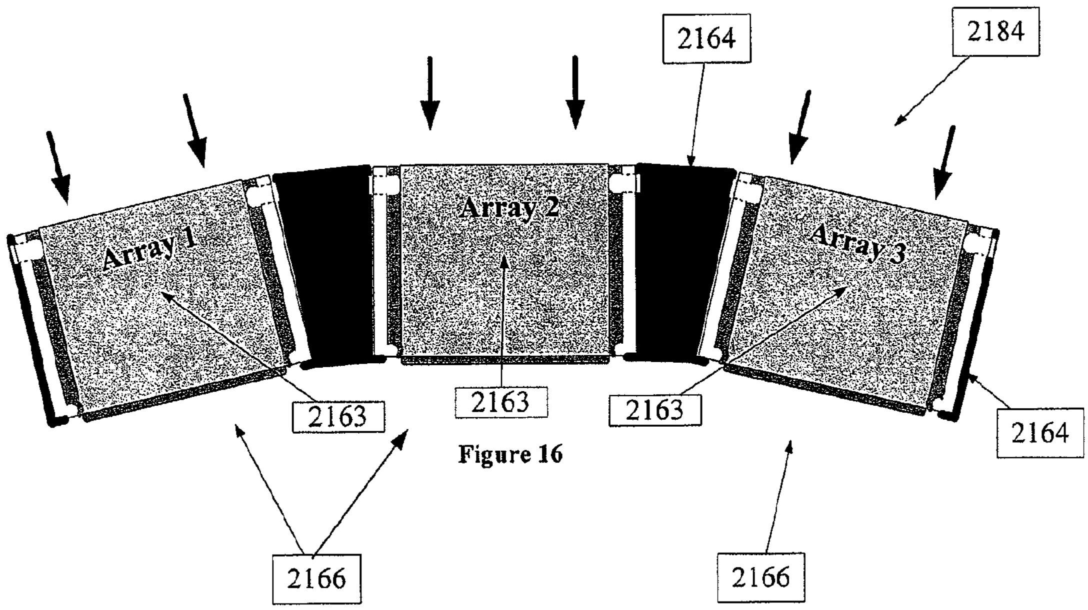
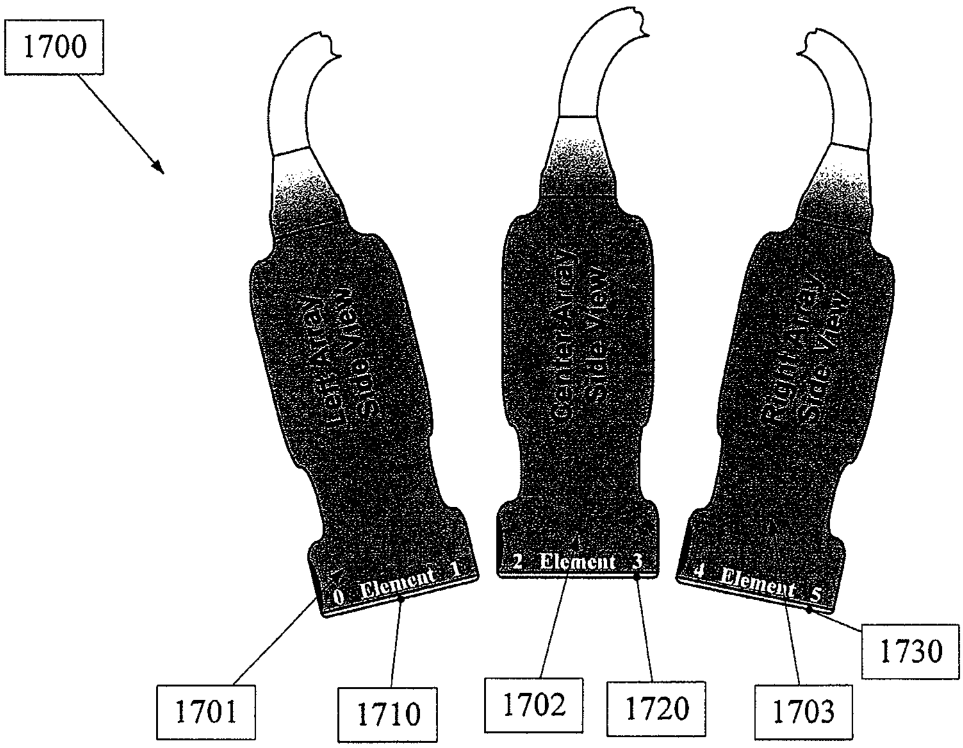


Figure 16

Figure 17


1700
Left Array
Side View
Center Array
Side View
Right Array
Side View
0 Element 1
2 Element 3
4 Element 5
1701
1710
1702
1720
1703
1730

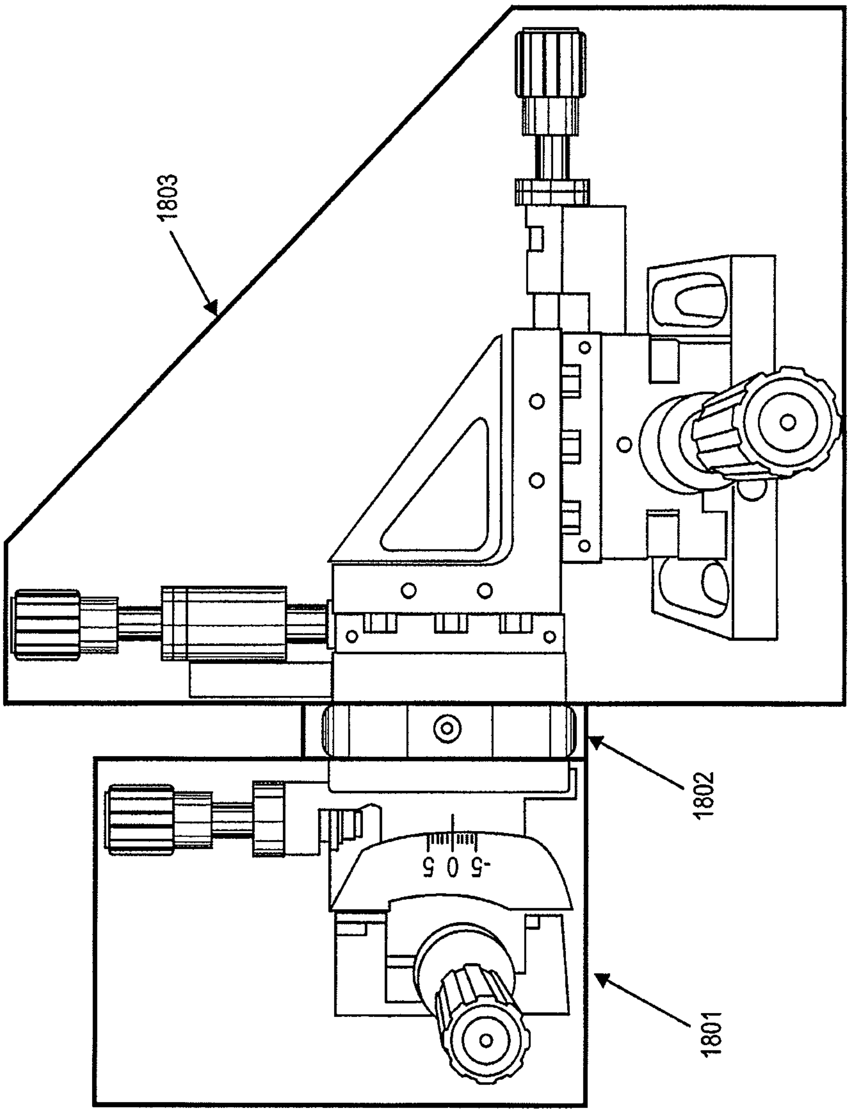


FIG. 18A

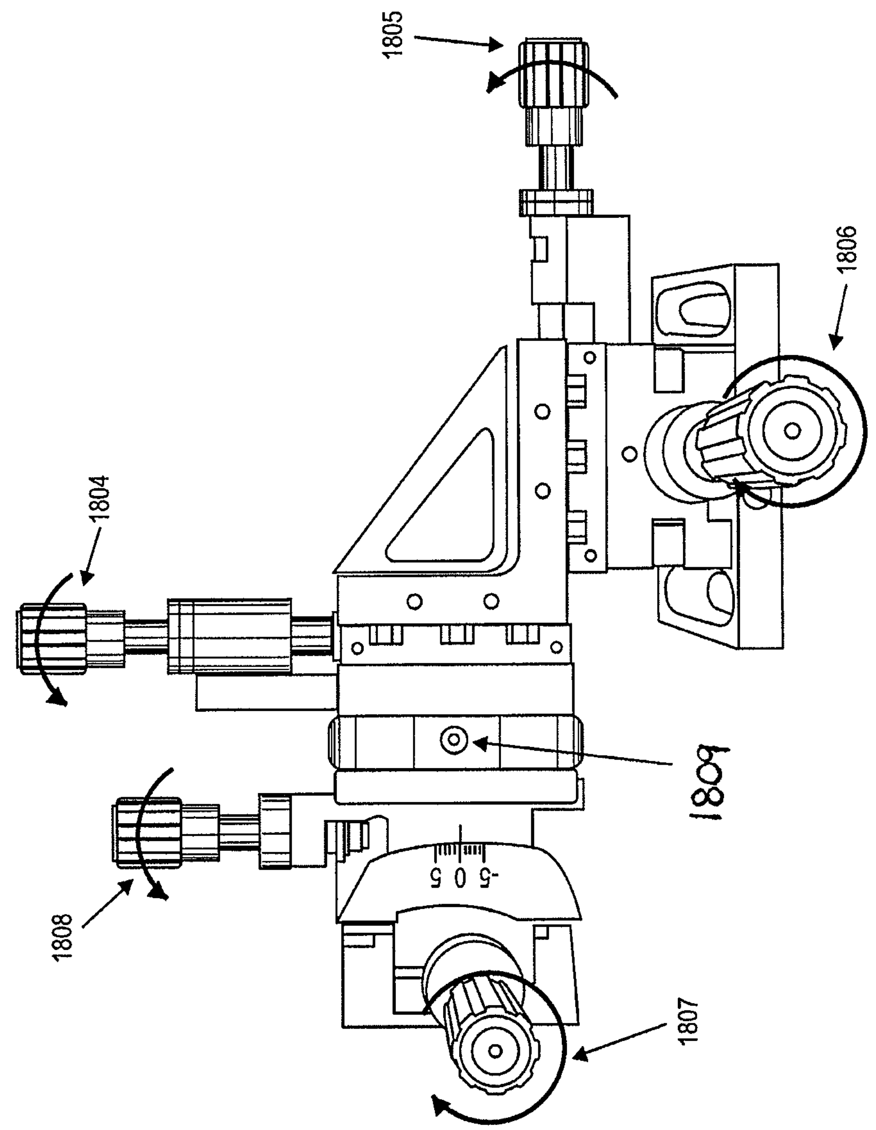


FIG. 18B

Figure 19a

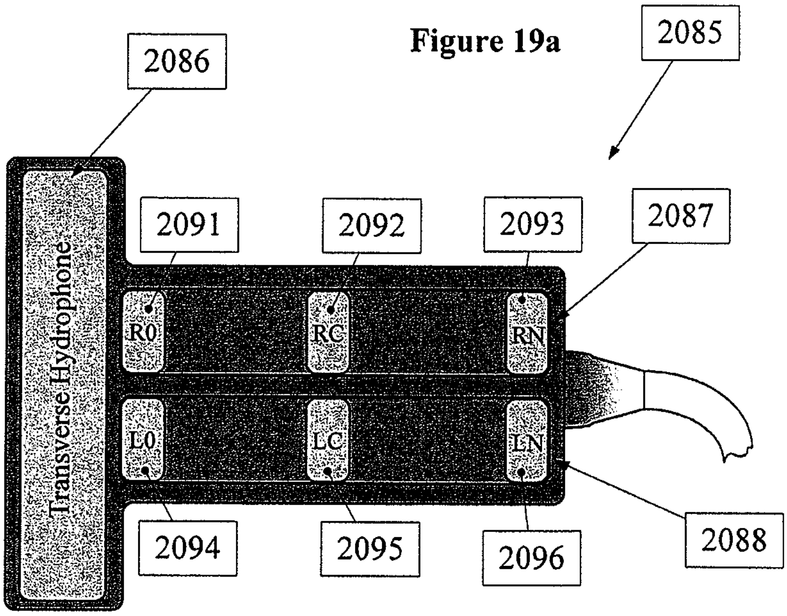


Figure 19b

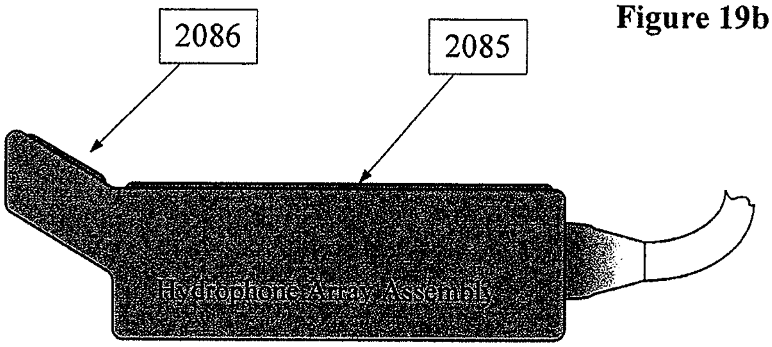
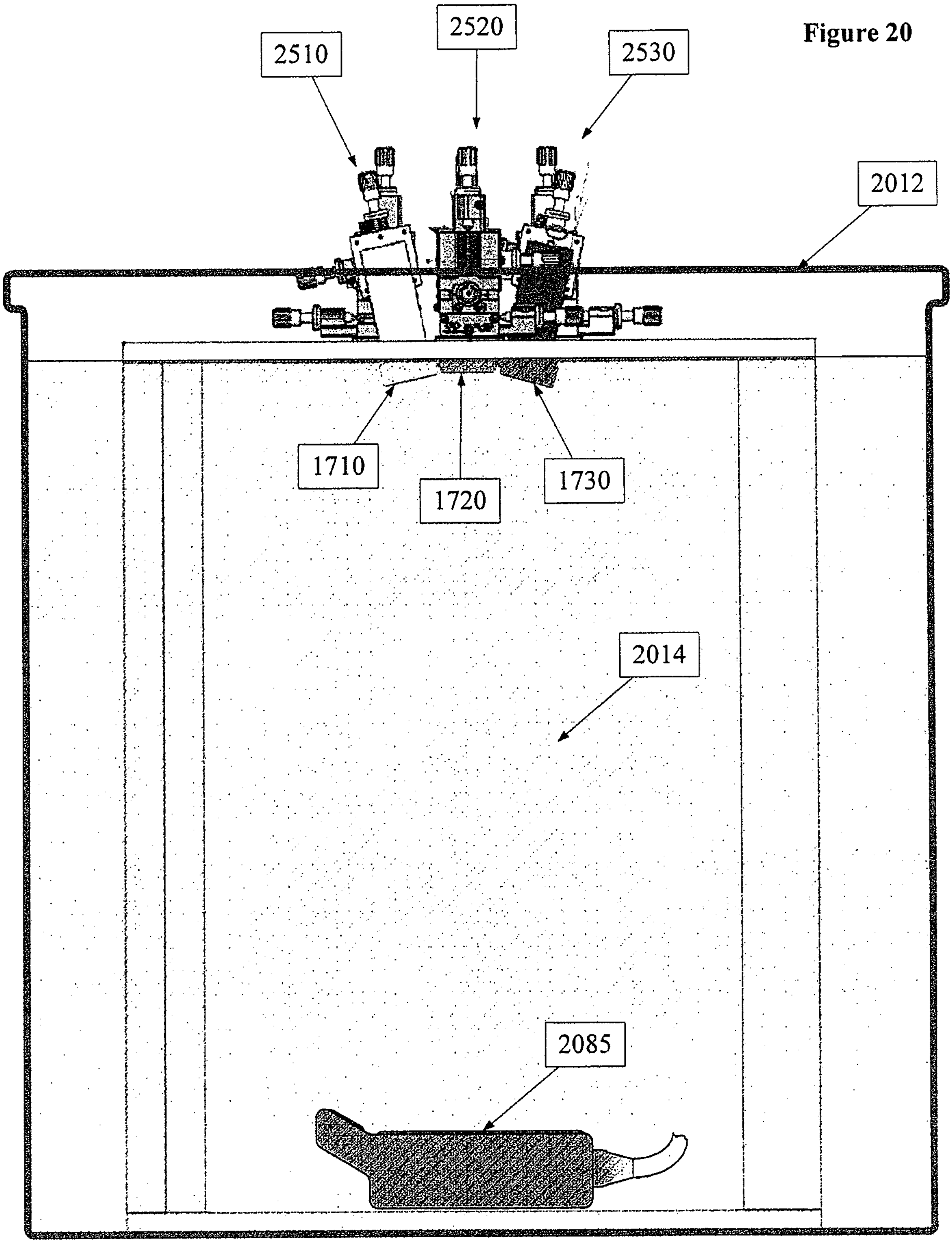


Figure 20



Assembled test fixture in tank.

Figure 21a

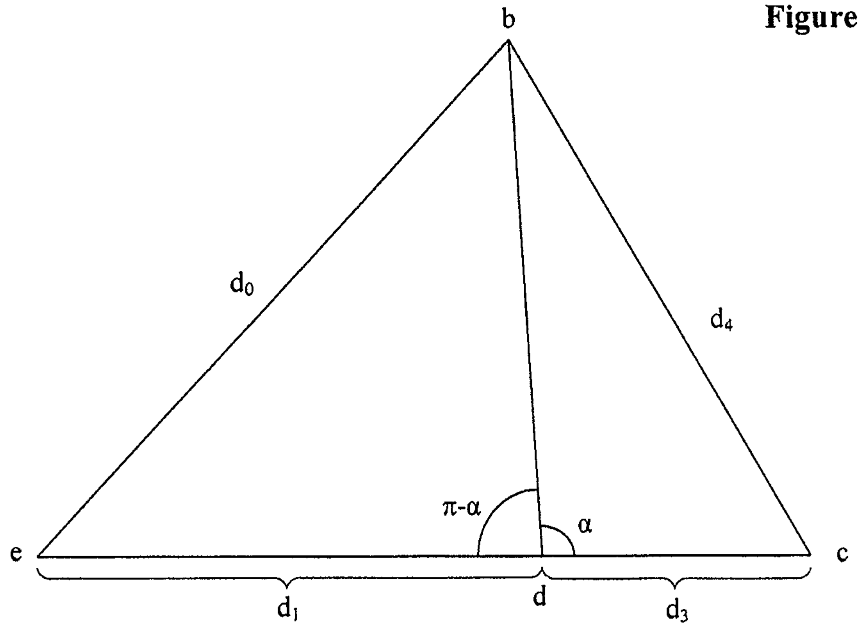
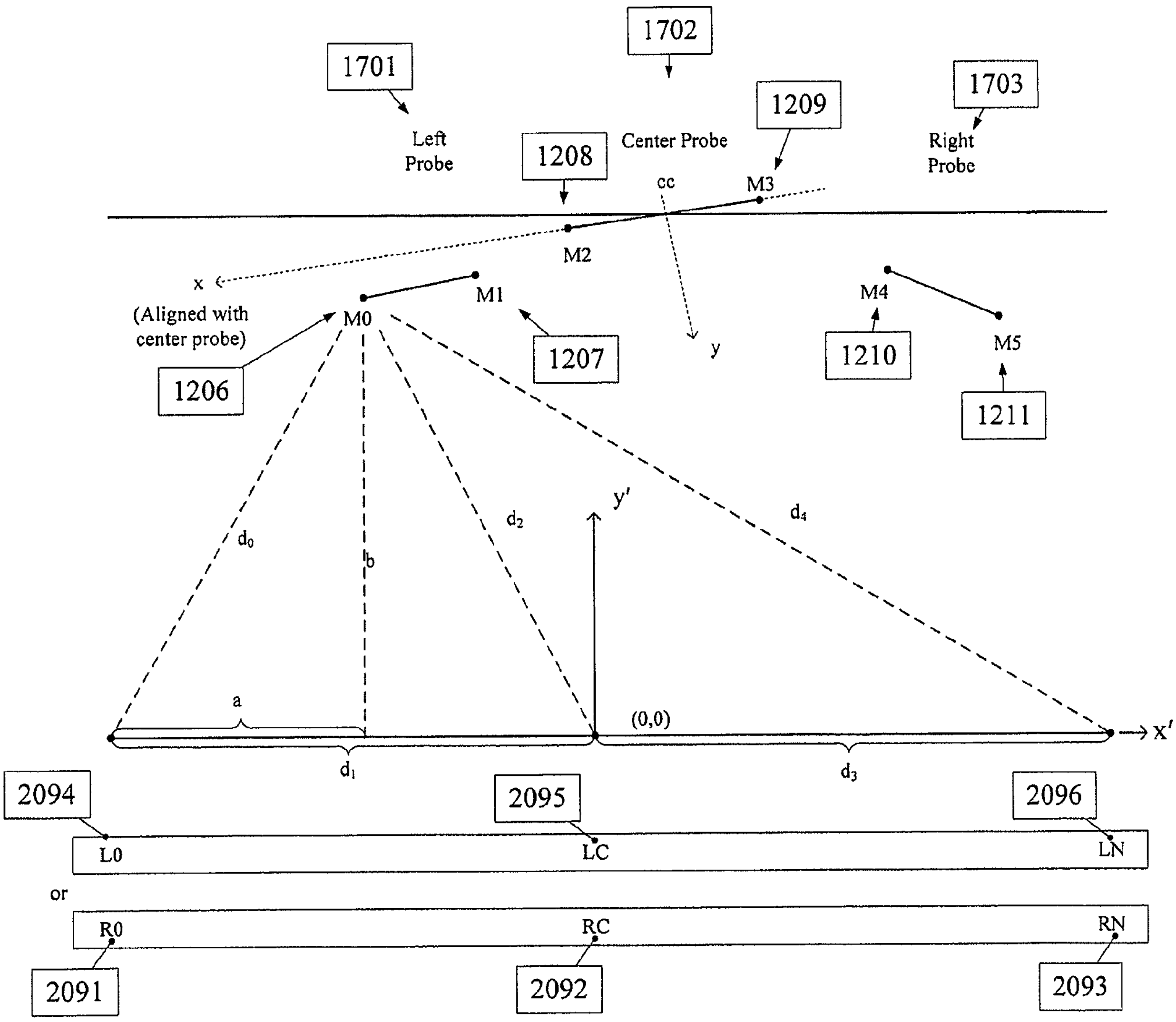


Figure 21b



First reference is LC or RC
Final reference is center of center probe (cc)

Figure 22

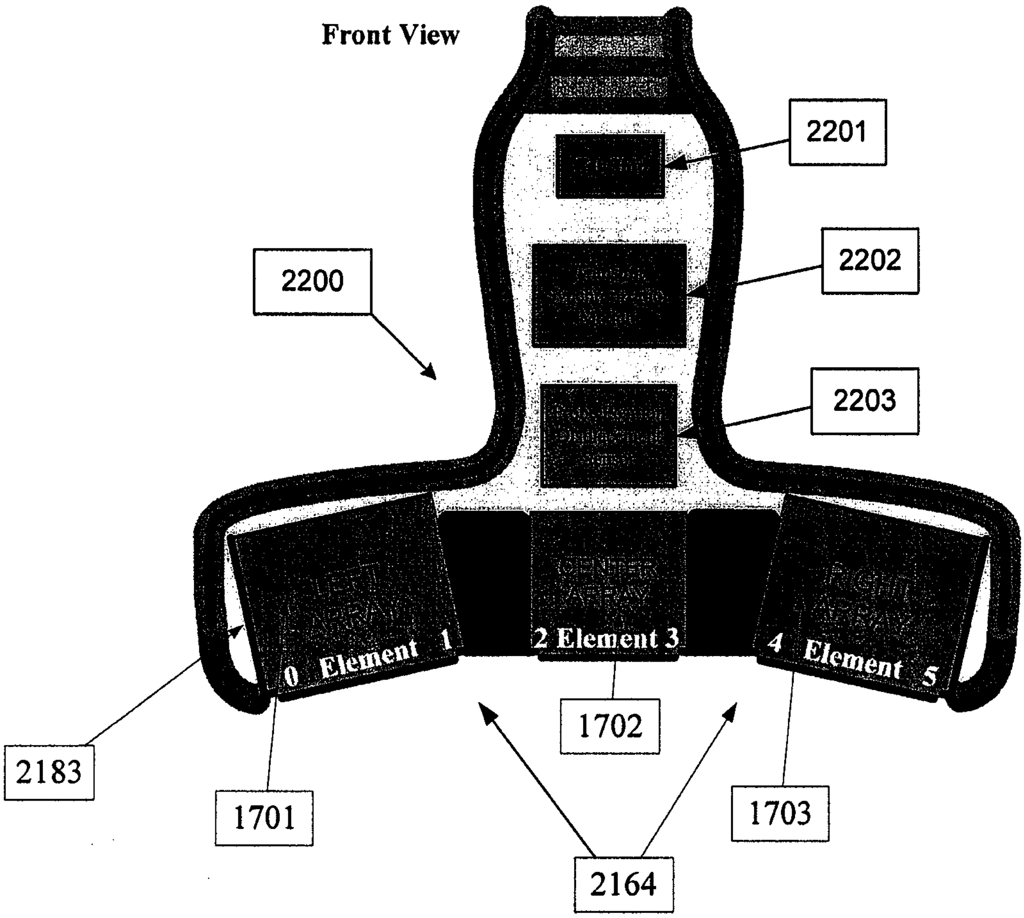

Front View
2201
2202
2200
2203
0 Element 1
2 Element 3
4 Element 5
2183
1701
1702
1703
2164

Figure 23a

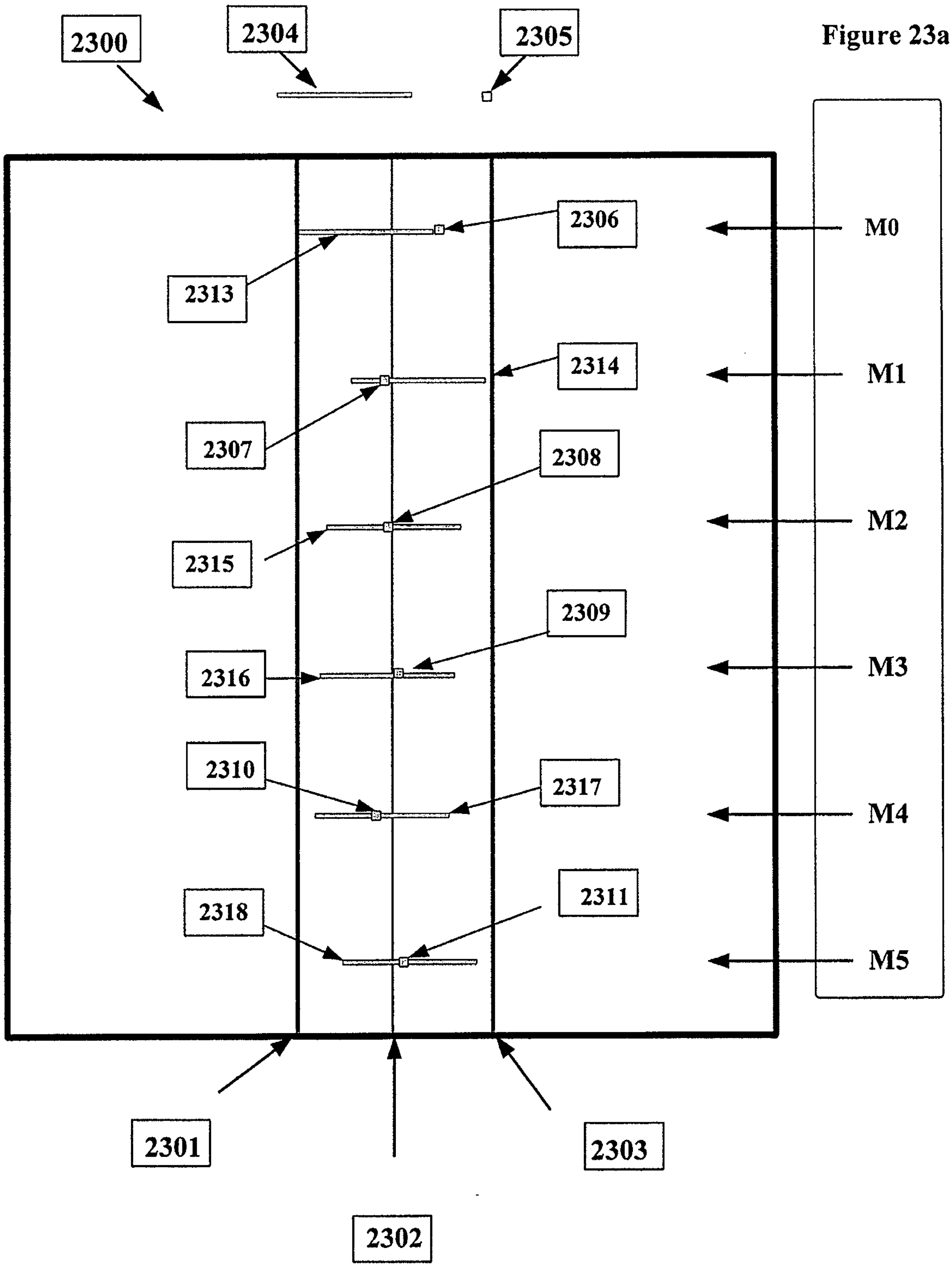

2300
2304
2305
2306
2313
2314
2307
2308
2315
2309
2316
2310
2317
2318
2311
M0
M1
M2
M3
M4
M5
2301
2302
2303

Figure 23b

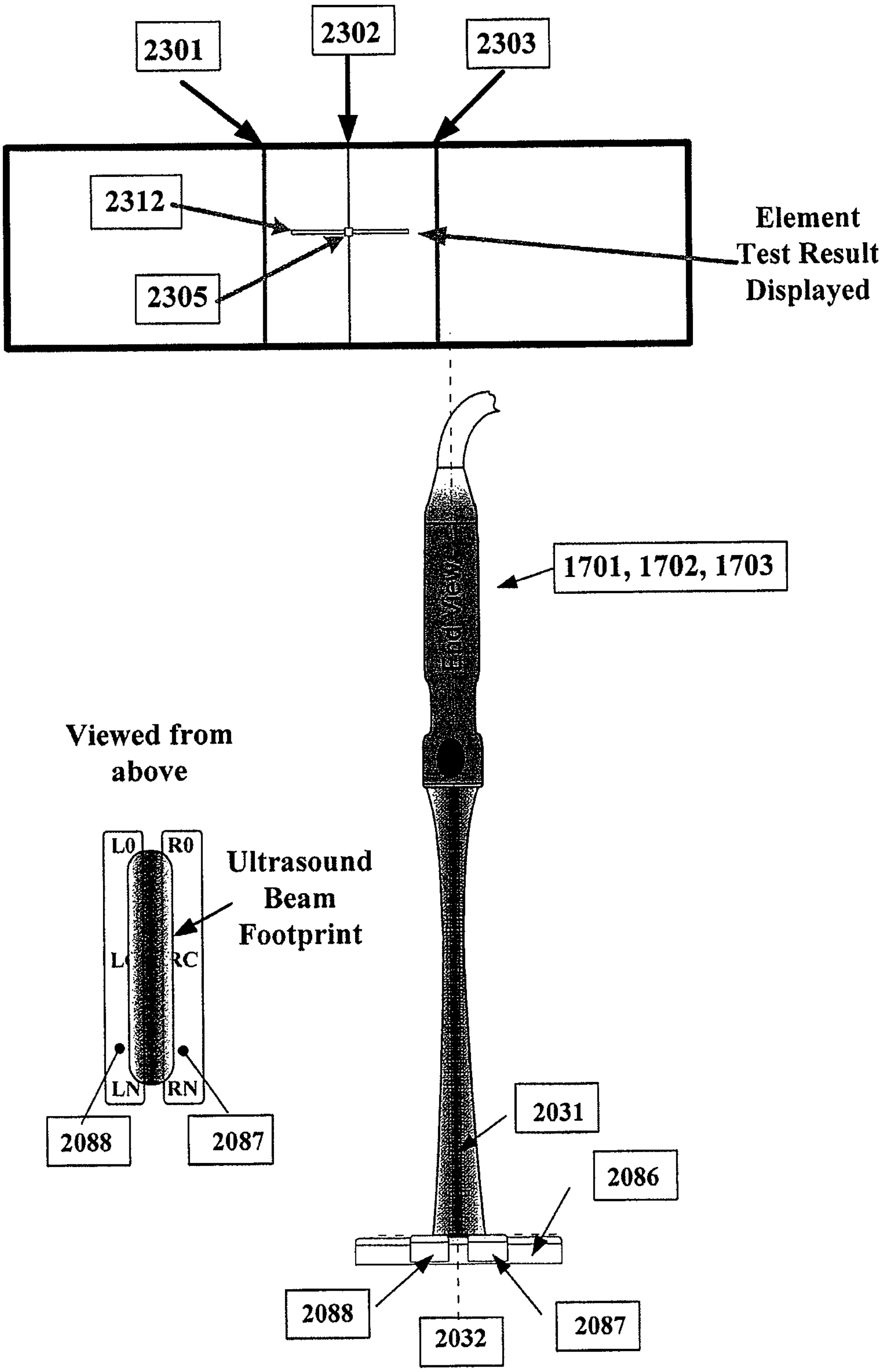

2301
2302
2303
2312
2305
Element
Test Result
Displayed
1701, 1702, 1703
Viewed from
above
L0
R0
Ultrasound
Beam
Footprint
RC
LN
RN
2088
2087
2031
2086
2088
2032
2087

Figure 23c

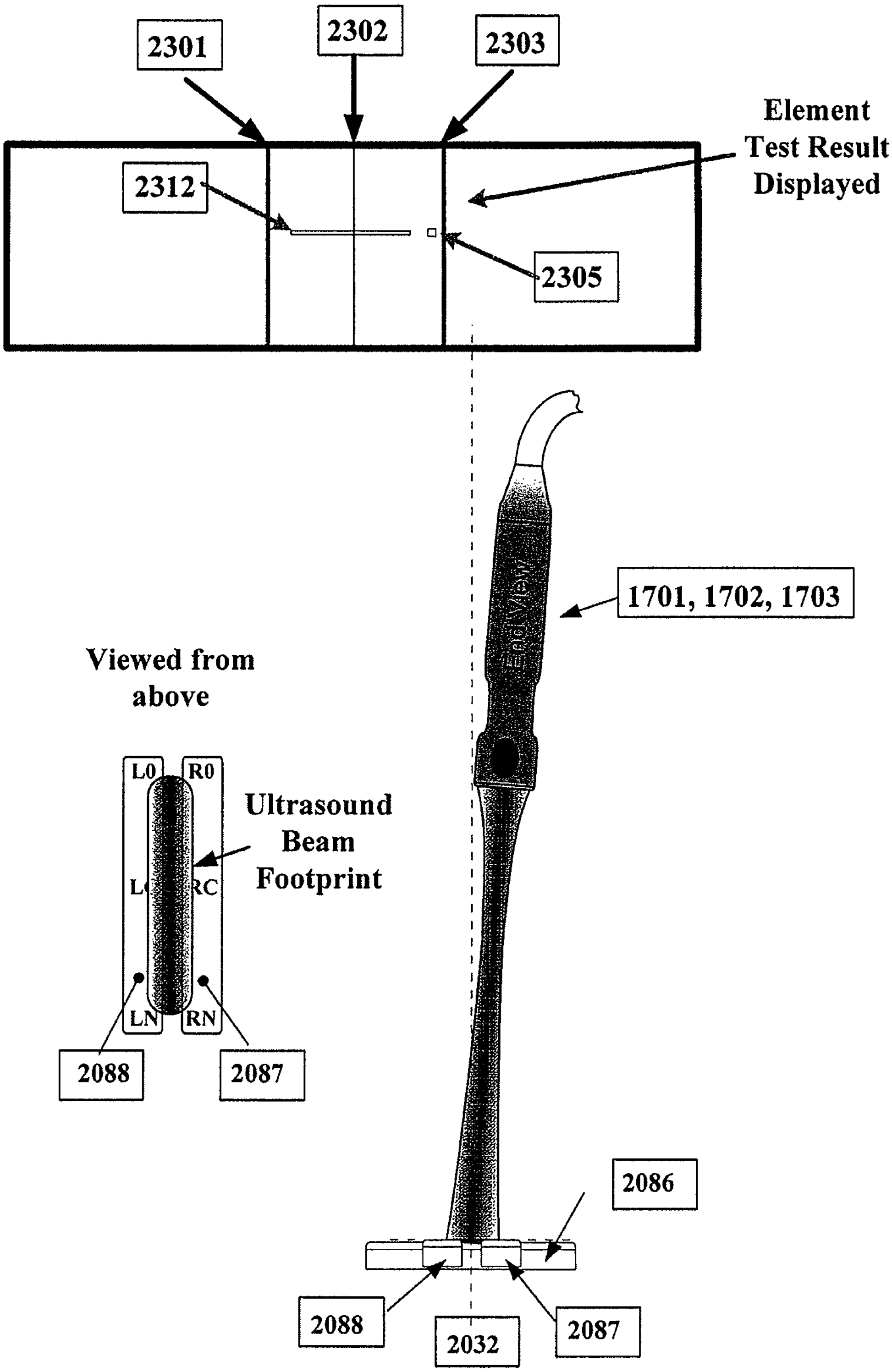

2301
2302
2303
Element Test Result Displayed
2312
2305
1701, 1702, 1703
EndView
Viewed from above
L0
R0
Ultrasound Beam Footprint
RC
LN
RN
2088
2087
2086
2088
2032
2087

Figure 23d

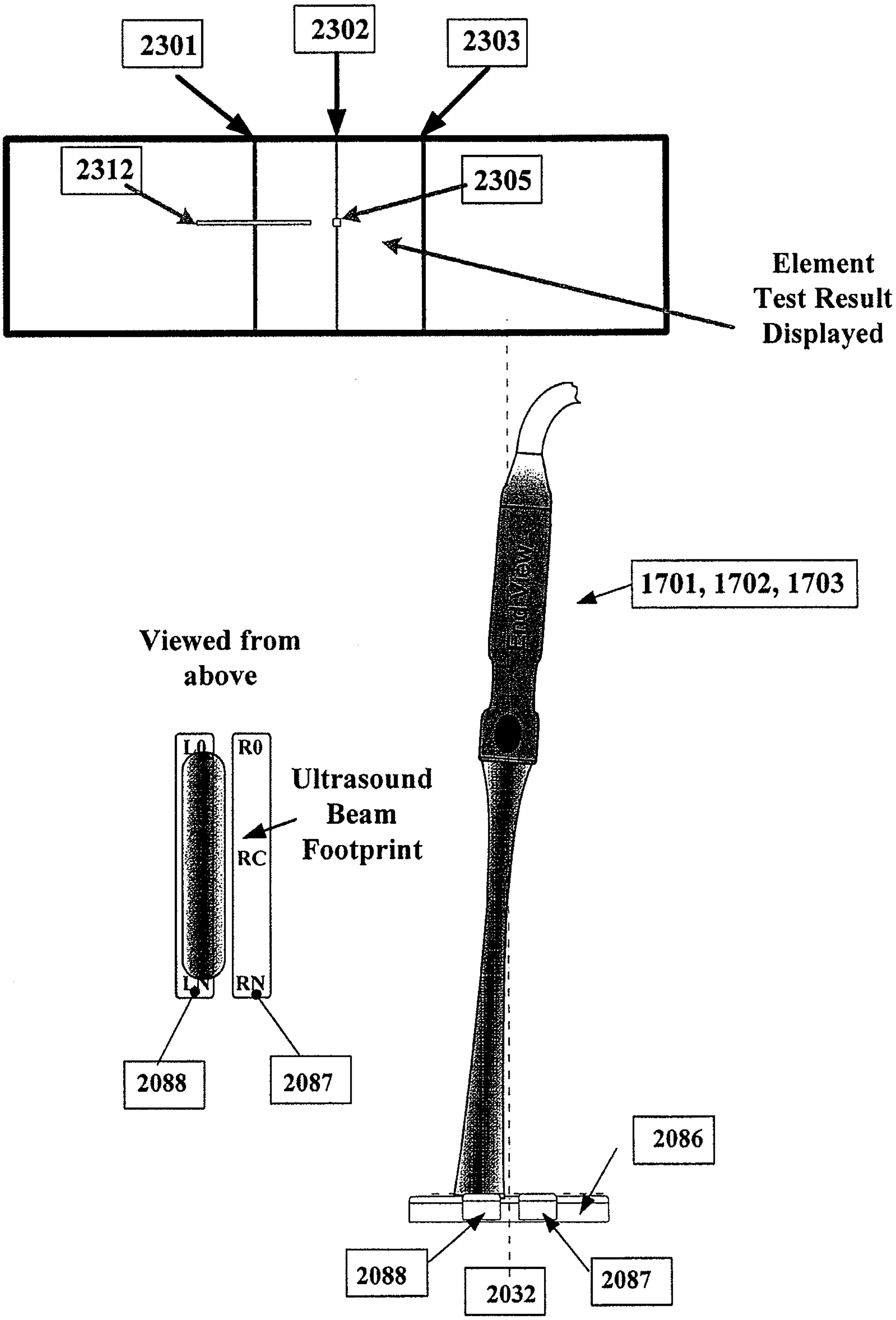
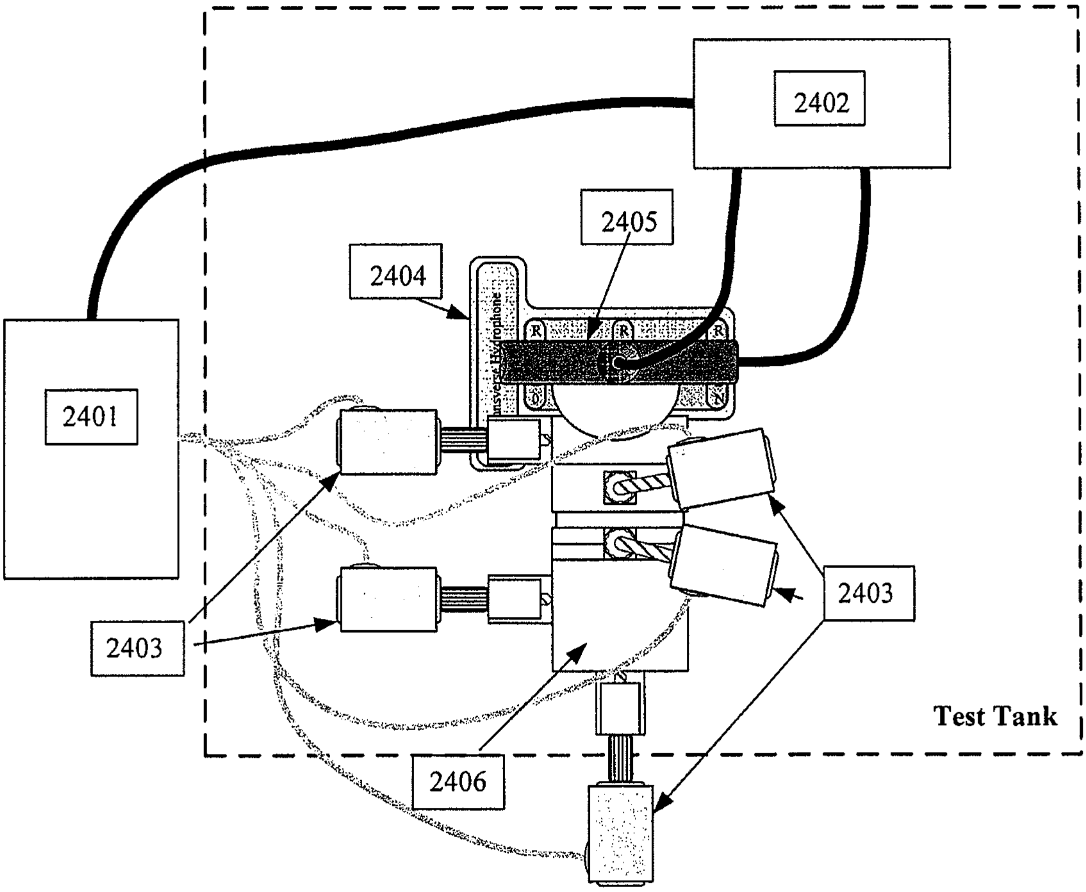

2301
2302
2303
2312
2305
Element
Test Result
Displayed
1701, 1702, 1703
Viewed from
above
L0
R0
Ultrasound
Beam
Footprint
RC
LN
RN
2088
2087
2086
2088
2032
2087

Figure 24

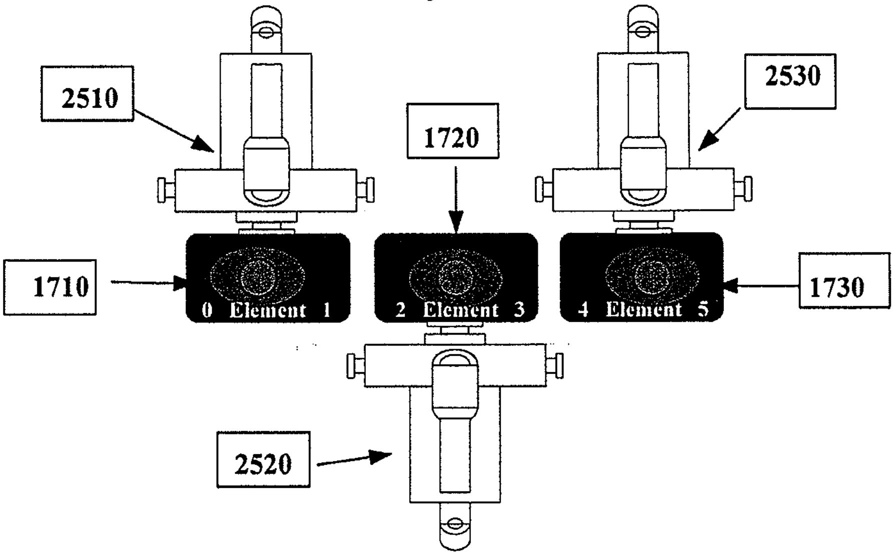
Top View



Automated Precision Stage
Assembly

Figure 25

Top View



Precision Alignment Stage Assembly

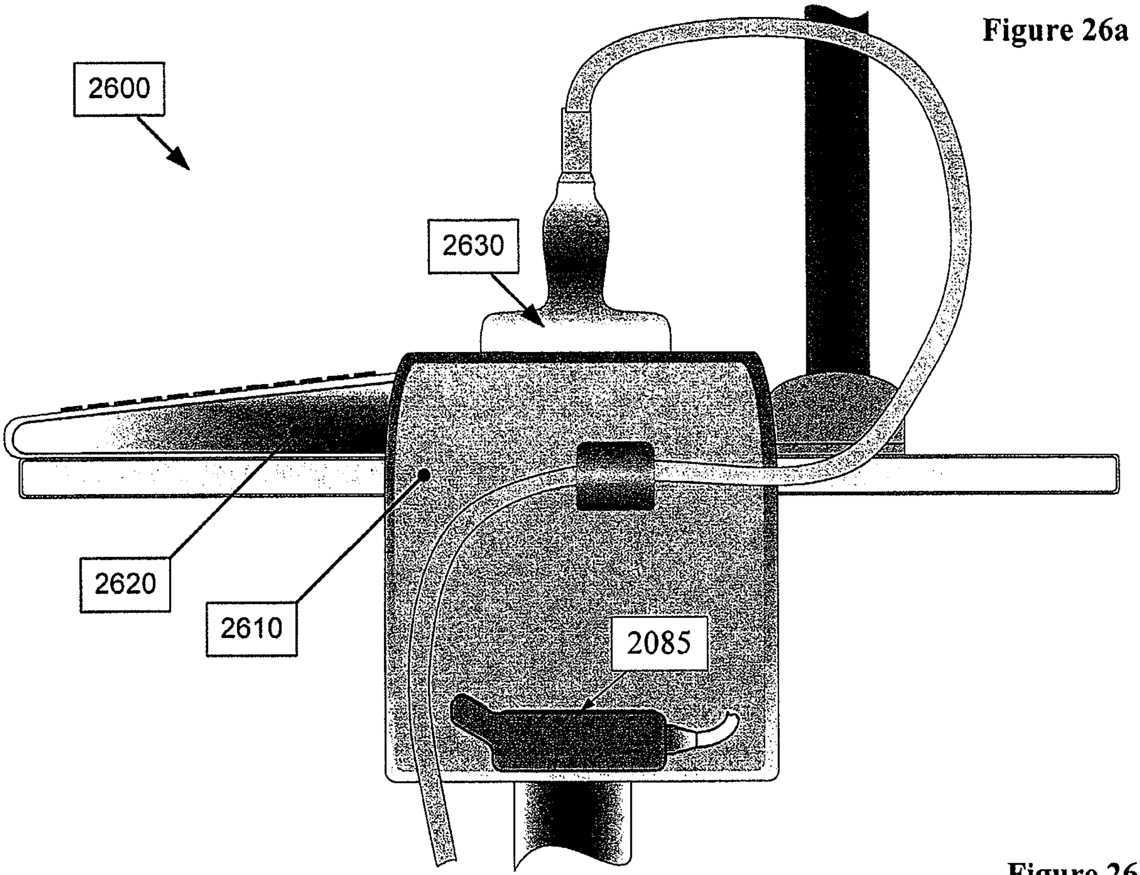


Figure 26a

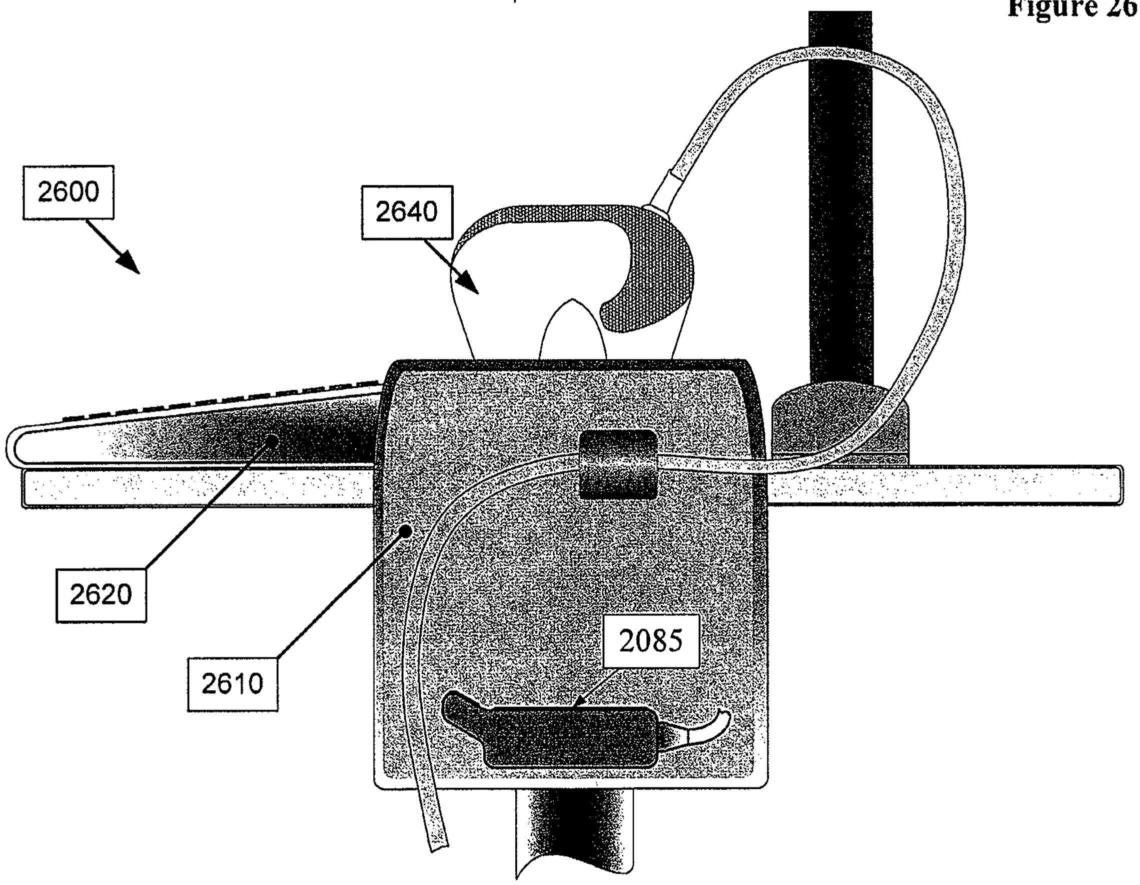


Figure 26b

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 5230339 A **[0007]**

Non-patent literature cited in the description

- **V A KRAMB et al.** Considerations for Using Phased Array Ultrasonics in a Fully Automated Inspection System. *AIP Conference Proceedings* **[0008]**

专利名称(译)	具有多个孔的超声波阵列的对准装置		
公开(公告)号	EP2419022B1	公开(公告)日	2019-11-06
申请号	EP2010765107	申请日	2010-04-14
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申请(专利权)人(译)	MAUI IMAGING , INC.		
当前申请(专利权)人(译)	MAUI IMAGING , INC.		
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摘要(译)

通过包括一个以上的探头并使用所有探头的元件来渲染图像来增加超声成像探头的有效孔径可以极大地提高所生成图像的横向分辨率。为了渲染图像，必须精确知道所有元素的相对位置。描述了一种校准夹具，其中将要校准的探针组件放置在测试块上方，并将超声脉冲通过测试块传输到超声传感器。当超声波脉冲通过要测试的探头中的某些或所有元件传输时，波形到达的差分传输时间将被精确测量。根据这些测量，可以计算出探针元件的相对位置，并且可以对准探针。