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# (54) Title: A NON-CONTACT ULTRASONIC DEVICE, A NON-CONTACT ULTRASONIC SYSTEM FOR DETERMINING AN INTRAOCULAR PRESSURE OF AN EYE AND A METHOD OF DETERMINING AN INTRAOCULAR PRESSURE OF AN EYE

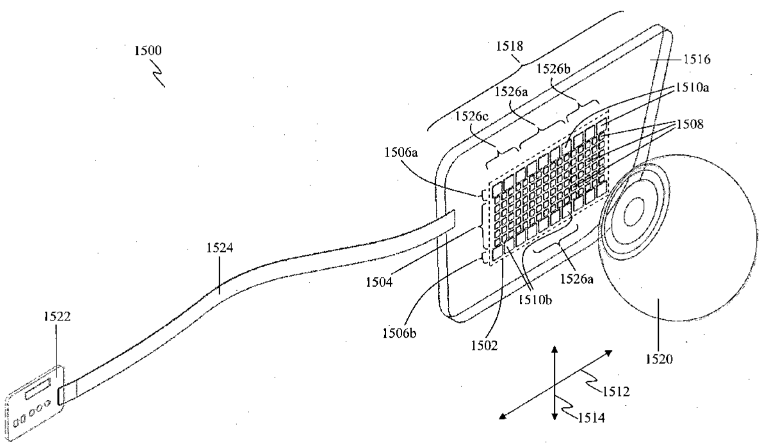


FIG. 15

**(57) Abstract**: According to embodiments of the present invention, a non-contact ultrasonic device is provided. The non-contact ultrasonic device includes a plurality of first elements configured to actuate a corneal surface of an eye; and a plurality of second elements configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface.

# A NON-CONTACT ULTRASONIC DEVICE, A NON-CONTACT ULTRASONIC SYSTEM FOR DETERMINING AN INTRAOCULAR PRESSURE OF AN EYE AND A METHOD OF DETERMINING AN INTRAOCULAR PRESSURE OF AN EYE

## Cross-Reference To Related Application

**[0001]** This application claims the benefit of priority of US provisional application No. 61/469,126, filed 30 March 2011, the content of it being hereby incorporated by reference in its entirety for all purposes.

## Technical Field

**[0002]** Various embodiments relate to a non-contact ultrasonic device, an ocular device comprising the non-contact ultrasonic device, a non-contact ultrasonic system for determining an intraocular pressure of an eye, a non-contact ultrasonic system for determining an information of an eye, a non-contact ultrasonic system for determining a topographic profile of a deformable structure, a non-contact ultrasonic device for actuating a deformable structure, a method of controlling a non-contact ultrasonic device, a method of determining an intraocular pressure of an eye, a method of determining an information of an eye, a method of determining a topographic profile of a deformable structure and a method of actuating a deformable structure.

## Background

**[0003]** The intraocular pressure (IOP) is defined as the pressure of aqueous humor enclosed inside the anterior chamber of human eyes, which is formed by the cornea, lens and iris. An elevated IOP is one of the major risk factors associated with the eye disorder glaucoma. Hence monitoring the IOP is one of the factors involved in the management of glaucoma.

**[0004]** The current gold standard of IOP measurement is based on the Goldmann Applanation Tonometer, which uses a probe to physically form an indentation on a corneal surface of an individual's eye. However, the Goldmann Applanation Tonometer and other existing IOP measurement approaches, such as pneumotometer and dynamic contour tonometer (DCT), have two major shortcomings. These include (i) the requirement of contact with a corneal surface of the individual's eye and (ii) measurements of the IOP without considering the corneal profile of the individual, which varies from one individual to another individual.

**[0005]** The direct contact with the corneal surface, both through a probe or through air-puff, introduces a concentrated external force on the corneal surface and consequently the cornea. This results in spontaneous contractions of the eyeball muscles, which in turn effectively changes the IOP, as a result of such contacts. In addition, the conventional IOP measurements do not consider the corneal profile difference between each individual, which further results in measurement errors due to the assumption that all individuals have the same corneal thickness and corneal radius curvature.

**[0006]** In addition, conventional approaches use a single ultrasonic transducer or a concavely focused ultrasonic transducer.

## Summary

**[0007]** According to an embodiment, a non-contact ultrasonic device is provided. The non-contact ultrasonic device may include a plurality of first elements configured to actuate a corneal surface of an eye; and a plurality of second elements configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface.

**[0008]** According to an embodiment, an ocular device is provided. The ocular device may include: a non-contact ultrasonic device.

**[0009]** According to an embodiment, a non-contact ultrasonic system for determining an intraocular pressure of an eye is provided. The non-contact ultrasonic system may include a non-contact ultrasonic device or an ocular device comprising a non-contact ultrasonic device; and a control module in electrical communication with the non-contact ultrasonic device, wherein the control module is configured to determine the intraocular pressure.

**[0010]** According to an embodiment, a method of controlling a non-contact ultrasonic device is provided. The method may include actuating a corneal surface of an eye; emitting a plurality of measurement ultrasonic beams on a point on the actuated corneal surface; and receiving a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface.

**[0011]** According to an embodiment, a non-contact ultrasonic system for determining an intraocular pressure of an eye is provided. The non-contact ultrasonic system may include a topographic profile determination circuit configured to determine a topographic profile of a corneal surface of the eye; a tensional force determination circuit configured to determine a tensional force of the corneal surface; and an intraocular pressure determination circuit configured to determine the intraocular pressure of the eye based on the tensional force and the topographic profile.

**[0012]** According to an embodiment, a method of determining an intraocular pressure of an eye is provided. The method may include determining a topographic profile of a corneal surface of the eye; determining a tensional force of the corneal surface; and determining the intraocular pressure of the eye based on the tensional force and the topographic profile.

**[0013]** According to an embodiment, a non-contact ultrasonic system for determining an intraocular pressure of an eye is provided. The non-contact ultrasonic system may include a topographic profile determination circuit configured to determine a topographic profile of a corneal surface of the eye; a plurality of first elements configured to actuate the corneal surface; a plurality of second elements configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface; and an intraocular pressure determination circuit configured to determine the intraocular pressure of the eye based on the plurality of measurement ultrasonic beams emitted, the reflected ultrasonic beam received and the topographic profile.

**[0014]** According to an embodiment, a method of determining an intraocular pressure of an eye is provided. The method may include determining a topographic profile of a corneal surface of the eye; actuating the corneal surface; emitting a plurality of measurement ultrasonic beams on a point on the actuated corneal surface; receiving a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the actuated corneal surface; and determining the intraocular pressure of the eye based on the plurality of measurement ultrasonic beams emitted, the reflected ultrasonic beam received and the topographic profile.

**[0015]** According to an embodiment, a non-contact ultrasonic system for determining an information of an eye is provided. The non-contact ultrasonic system may include a plurality of elements configured to emit a plurality of ultrasonic beams on a point on a corneal surface of the eye, and further configured to receive a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the corneal surface; and a control module in electrical communication with the plurality of elements, wherein the control module is configured to determine a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam to determine the information.

**[0016]** According to an embodiment, a method of determining an information of an eye is provided. The method may include emitting a plurality of ultrasonic beams on a point on a corneal surface of the eye; receiving a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the corneal surface; and determining a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam to determine the information.

**[0017]** According to an embodiment, a non-contact ultrasonic system for determining a topographic profile of a deformable structure is provided. The non-contact ultrasonic device may include a plurality of elements configured to emit a plurality of ultrasonic beams on a point on a surface of the deformable structure, and further configured to receive a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the surface; and a control module in electrical communication with the plurality of elements, wherein the control module is configured to determine positions of the plurality of elements to determine the topographic profile.

**[0018]** According to an embodiment, a method of determining a topographic profile of a deformable structure is provided. The method may include emitting a plurality of ultrasonic beams from a first active group of a plurality of elements on a point on a surface of the deformable structure; receiving a reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the surface with a first passive group of the plurality of elements; and determining positions of the first active group and the first passive group to determine the topographic profile.

**[0019]** According to an embodiment, a non-contact ultrasonic device for actuating a deformable structure is provided. The non-contact ultrasonic device may include a plurality of first elements configured to emit a plurality of first ultrasonic beams having a first frequency at a surface of the deformable structure; and a plurality of second elements configured to emit a plurality of second ultrasonic beams having a second frequency at the surface of the deformable structure, wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency, and wherein the deformable structure is effectively actuated at the third frequency.

**[0020]** According to an embodiment, a method of actuating a deformable structure is provided. The method may include emitting a plurality of first ultrasonic beams having a first frequency for generating a first ultrasonic pressure, $P_1$, at a surface of the deformable structure; and emitting a plurality of second ultrasonic beams having a second frequency for generating a second ultrasonic pressure, $P_2$, at the surface of the deformable structure, wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency.

## Brief Description of the Drawings

**[0021]** In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

**[0022]** FIG. 1 shows a schematic block diagram of a non-contact ultrasonic device, according to various embodiments.

**[0023]** FIG. 2 shows a schematic block diagram of an ocular device, according to various embodiments.

**[0024]** FIG. 3A shows a schematic block diagram of a non-contact ultrasonic system for determining an intraocular pressure of an eye, according to various embodiments.

**[0025]** FIG. 3B shows a schematic block diagram of a non-contact ultrasonic system for determining an intraocular pressure of an eye, according to various embodiments.

**[0026]** FIG. 4 shows a flow chart illustrating a method of controlling a non-contact ultrasonic device, according to various embodiments.

**[0027]** FIG. 5 shows a schematic block diagram of a non-contact ultrasonic system for determining an intraocular pressure of an eye, according to various embodiments.

**[0028]** FIG. 6 shows a flow chart illustrating a method of determining an intraocular pressure of an eye, according to various embodiments.

**[0029]** FIG. 7 shows a schematic block diagram of a non-contact ultrasonic system for determining an intraocular pressure of an eye, according to various embodiments.

**[0030]** FIG. 8A shows a flow chart illustrating a method of determining an intraocular pressure of an eye, according to various embodiments.

**[0031]** FIG. 8B shows a flow chart illustrating a method of determining an intraocular pressure of an eye, according to the embodiment of FIG. 8A.

**[0032]** FIG. 9 shows a schematic block diagram of a non-contact ultrasonic system for determining an information of an eye, according to various embodiments.

**[0033]** FIG. 10 shows a flow chart illustrating a method of determining an information of an eye, according to various embodiments.

**[0034]** FIG. 11 shows a schematic block diagram of a non-contact ultrasonic system for determining a topographic profile of a deformable structure, according to various embodiments.

**[0035]** FIG. 12 shows a flow chart illustrating a method of determining a topographic profile of a deformable structure, according to various embodiments.

**[0036]** FIG. 13 shows a schematic block diagram of a non-contact ultrasonic device for actuating a deformable structure, according to various embodiments.

**[0037]** FIG. 14 shows a flow chart illustrating a method of actuating a deformable structure, according to various embodiments.

**[0038]** FIG. 15 shows a perspective view of a non-contact ultrasonic system comprising a non-contact ultrasonic device, according to various embodiments.

[0039] FIG. 16 shows cross-sectional views of a method to determine a topographic profile of a corneal surface of an eye, according to various embodiments.

[0040] FIG. 17 shows a cross-sectional view of a method to determine a thickness at an incident point of a corneal surface of an eye, according to various embodiments.

## Detailed Description

[0041] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0042] Various embodiments provide an intraocular pressure (IOP) measurement approach, without or with reduced at least some of the associated disadvantages of conventional devices and approaches. Various embodiments may provide a non-contact measurement approach for the eye, with minimal intervention on the movement of the eyeball. Various embodiments may achieve non-contact with the eye by incorporating an air-coupled approach. In addition, the approach of various embodiments take into account a corneal curvature profile and a corneal thickness profile of an eye of an individual.

[0043] Various embodiments may provide a device, a system and a method for the measurements of ocular properties (e.g. an intraocular pressure and/or a topographic profile of a corneal surface) using an array of air-coupled ultrasonic transducers.

[0044] Various embodiments may provide a non-contact intraocular pressure (IOP) measurement device, system and method, using an array of air-coupled ultrasonic transducers. In various embodiments, the measurement device, system and method may be used for performing *in-vivo* measurements. As the array of ultrasonic transducers are air-coupled, only ambient air is necessary for performing the measurements.

[0045] In various embodiments, the measurement device and system may include an array of dual frequency air-coupled ultrasonic transducers. In various embodiments, the ultrasonic or acoustic beams emitted from the array of ultrasonic transducers are steered and focused through the use of array beam-forming technology. Beam-forming is a technique used in sensor arrays for directional signal transmission or reception.

[0046] In various embodiments, the measurement device and system may include one or more front-end circuits integrated with the array of dual frequency air-coupled ultrasonic transducers. The measurement device and system may also include a control module, a digital signal processing module and a measurement display means. In various embodiments, the digital signal processing module may be integrated in the control module or provided as a separate module. In various embodiments, the measurement display means may be a display screen or a display unit, integrated with the measurement device and system of various embodiments, or provided separately.

[0047] In various embodiments, the array of ultrasonic transducers may be bonded on glass spectacles or glass goggles (for example on a surface of the glass) and worn or placed in proximity with a corneal surface of an eye of an individual.

[0048] In various embodiments, the array of ultrasonic transducers may be used to measure or determine a topographic profile (e.g. a curvature profile and/or a thickness profile) of a corneal surface of an eye to facilitate measurement of the IOP, with enhanced accuracy. Subsequently, the array of ultrasonic transducers may be used to determine a tensional force of the corneal surface, in order to determine the IOP based on the tensional force and the topographic profile of the corneal surface. Accordingly, the topographic profile, such as the curvature profile and/or the thickness profile of the corneal surface, may be determined before the IOP measurement and are considered when determining the IOP. In various embodiments, the tensional force of the corneal surface may also give a measurement of the tensional force among the corneal structures of the eye.

[0049] In various embodiments, the tensional force of the corneal surface may be determined using two independent approaches. The first approach is to detect or determine the resonant frequencies of the corneal surface. The resonant frequencies of the corneal surface may be determined from the corneal surface velocity. The second approach is to monitor or determine the impedance of the corneal surface. The impedance may be determined from a reflectance of the corneal surface.

**[0050]** In various embodiments, the arrangement or configuration of the array of ultrasonic transducers may be provided to cover at least a substantial portion of the corneal surface for determining the intraocular pressure (IOP). This may alleviate or relax the alignment requirement of the array of ultrasonic transducers to the central position of the corneal surface or cornea, thereby improving the robustness of the measurement.

**[0051]** Various embodiments may provide a device, system or method of determining an intraocular pressure of an eye, including an array of dual frequency air-coupled ultrasonic transducers for actuating and sensing the corneal surface or cornea through ultrasonic beams. In various embodiments, the array of dual frequency air-coupled ultrasonic transducers includes a plurality of first elements and a plurality of second elements, where the plurality of first elements have a different size or dimensions (e.g. an area) and a different central frequency to the plurality of second elements.

**[0052]** Various embodiments may provide a portable device or system. The portable device or system may be used for continual or semi-continuous measurement of the IOP during the periods when an individual's eye remains open.

**[0053]** Various embodiments may provide a method of measuring or determining an intraocular pressure (IOP), by determining a topographic profile of a corneal surface, such as a corneal curvature profile and a corneal thickness profile, and detecting the corneal surface resonant frequencies or structural resonant frequencies, in order to determine the IOP.

**[0054]** Various embodiments may provide a method of monitoring a fluctuation of an intraocular pressure (IOP) by monitoring or analyzing variations or changes of amplitudes in the acoustic signals reflected from a corneal surface.

**[0055]** In the context of various embodiments, the term 'ultrasonic' as applied to ultrasonic waves mean that the waves have a frequency greater than the upper limit of human hearing (e.g. a frequency greater than approximately 20 kHz). Ultrasonic waves are sound waves and therefore, in the context of various embodiments, the term 'ultrasonic' may be used interchangeably with the term 'acoustic'.

[0056] In the context of various embodiments, the terms 'ultrasonic waves' and 'ultrasonic beams' may be used interchangeably.

[0057] In the context of various embodiments, the term 'actuation element' may mean an element that is configured to emit an ultrasonic beam to actuate a corneal surface of an eye, a membrane or any deformable structure.

[0058] In the context of various embodiments, the term 'measurement element' may mean an element that is configured to emit an ultrasonic beam to facilitate measurement of a property of a corneal surface of an eye, a membrane or any deformable structure.

[0059] In the context of various embodiments, the term 'active element' may mean an element that is actuated to emit an ultrasonic beam.

[0060] In the context of various embodiments, the term 'passive element' may mean an element that is not actuated to emit an ultrasonic beam. A passive element may also receive a reflected ultrasonic beam.

[0061] In various embodiments, the array of elements of the ultrasonic device are passive elements. When a number of elements are activated, these elements switch to being active elements and are actuated to emit ultrasonic beams. Subsequently after emitting and transmitting the ultrasonic beams, these active elements may switch back to being passive elements. In various embodiments when measurements are performed, the term 'active group' refers to a group of one or more elements configured to emit a plurality of ultrasonic beams while the term 'passive group' refers to a group of one or more elements configured to receive the reflected ultrasonic beam.

[0062] In the context of various embodiments, the term 'topographic profile' as applied to the corneal surface may include at least one of a curvature profile and a thickness profile of the corneal surface.

[0063] In the context of various embodiments, the term 'corneal surface' may include the surface of the cornea or the cornea itself.

[0064] In the context of various embodiments, the term 'tensional force' as applied to a corneal surface may mean a tangential force along the corneal surface, as a result of intraocular pressure.

[0065] In the context of various embodiments, the term 'corneal surface velocity' may mean a radial velocity normal to the corneal surface, as a result of acoustic actuation. The corneal surface velocity is a function of geometrical coordinates and therefore may be different at different positions on the corneal surface.

**[0066]** In the context of various embodiments, the term 'resonant frequencies' as applied to a corneal surface may mean the frequencies at which the corneal surface or cornea vibrates at its maximum amplitude (i.e. resonance). The corneal surface may experience resonance when external excitations oscillating at frequencies corresponding to the resonant frequencies of the corneal surface are applied to the corneal surface.

**[0067]** In the context of various embodiments, the term 'impedance' as applied to a corneal surface may mean a ratio of an acoustic pressure to a velocity along the corneal surface. The acoustic pressure on the corneal surface is a function of geometrical coordinates and therefore may be different at different positions on the corneal surface.

**[0068]** In the context of various embodiments, one or more front-end integrated circuits (IC) may be provided in electrical communication with the array of ultrasonic transducers.

**[0069]** In the context of various embodiments, the word 'circuit' as applied in the term 'determination circuit' may include a circuit, a device, a component, an element, a module or the likes.

**[0070]** In the context of various embodiments, a 'circuit' may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a 'circuit' may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g. a microprocessor (e.g. a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A 'circuit' may also be a processor executing software, e.g. any kind of computer program, e.g. a computer program using a virtual machine code such as e.g. Java. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a 'circuit' in accordance with an alternative embodiment.

**[0071]** In the context of various embodiments, any reference made to a reflected ultrasonic beam, also include a reference to a plurality of reflected ultrasonic beams.

[0072] In the context of various embodiments, the term 'deformable structure' may include a membrane or a corneal surface of an eye.

[0073] In order that the invention may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

[0074] It should be appreciated that descriptions relating to an embodiment of a device or a system may similarly be applicable to other embodiments of a device or a system. Similarly, descriptions relating to an embodiment of a method may similarly be applicable to other embodiments of a method. In addition, it should be appreciated that descriptions relating to embodiments of a device or a system may similarly be applicable to embodiments of a method and vice versa.

[0075] FIG. 1 shows a schematic block diagram of a non-contact ultrasonic device 100, according to various embodiments. The non-contact ultrasonic device 100 includes a plurality of first elements 102 configured to actuate a corneal surface of an eye, and a plurality of second elements 104 configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface. The plurality of first elements 102 may be configured to emit a plurality of actuation ultrasonic beams to actuate the corneal surface. In various embodiments, the plurality of second elements 104 may also be configured to actuate the corneal surface of an eye.

[0076] The plurality of first elements 102 may emit a plurality of actuation ultrasonic beams having a first frequency and the plurality of second elements 104 may emit a plurality of measurement ultrasonic beams having a second frequency, wherein the second frequency is higher than the first frequency.

[0077] Each of the plurality of first elements 102 may have a first size and each of the plurality of second elements 104 may have a second size. In various embodiments, the first size of the plurality of first elements 102 and the second size of the plurality of second elements 104 may be at least substantially same. In further embodiments, the first size of the plurality of first elements 102 and the second size of the plurality of second elements 104 may be different. As a non-limiting example, the first size of the plurality of first elements 102 may be larger than the second size of the plurality of second elements 104. Therefore, the plurality of first elements 102 may refer to larger elements emitting actuation ultrasonic beams with a low ultrasonic central frequency while the plurality of second elements 104 may refer to smaller elements emitting measurement ultrasonic beams with a high ultrasonic central frequency.

**[0078]** The plurality of second elements 104 may be arranged in a first grid pattern extending in a first direction and a second direction, wherein a number of the plurality of second elements 104 in the first direction is higher than in the second direction. In various embodiments, the plurality of first elements 102 may be arranged in a second grid pattern on a first side and a second side of the first grid pattern of the plurality of second elements 104 in the second direction.

**[0079]** The plurality of first elements 102 may be configured to actuate the corneal surface or the corneal structures dynamically. Hereinafter, the plurality of such elements may be referred to as the 'actuation elements'.

**[0080]** The plurality of second elements 104 may be configured to focus and steer the acoustic or ultrasonic beams emitted from the plurality of second elements 104 to the desired point or position on a corneal surface of an eye through an array beam-forming technology, and may be used to determine or measure corneal properties, for example the topographic profile of the corneal surface. Hereinafter, the plurality of such elements may be referred to as the 'measurement elements'.

**[0081]** In the context of various embodiments, the plurality of first elements 102 or the actuation elements may have a shape of a square or a rectangle. In various embodiments, the plurality of first elements 102 may have a width of between about 30 mm to about 50 mm, a length of between about 30 mm to about 50 mm and a height of about 3 mm. However, it should be appreciated that the plurality of first elements 102 may have other sizes or shapes, for example the shape of a circle, a sphere, an oval or a polygon.

**[0082]** In the context of various embodiments, the plurality of first elements 102 or the actuation elements may emit ultrasonic beams with a central frequency (i.e. the first frequency) of above 100 kHz, for example in a range of between about 100 kHz to about 5 MHz (5000 kHz), for example a range of between about 100 kHz to about 3 MHz, a range of between about 100 kHz to about 1 MHz, a range of between about 100 kHz to about 500 kHz, a range of between about 500 kHz to about 5 MHz, a range of between about 500 kHz to about 3 MHz, a range of between about 500 kHz to about 1.6 MHz or a range of between about 1.6 MHz to about 5 MHz, such that the ultrasonic beams may have a central frequency of about 100 kHz, about 200 kHz, about 300 kHz, about 500 kHz, about 1 MHz, about 1.6 MHz, about 3 MHz, or about 5 MHz.

**[0083]** In the context of various embodiments, the plurality of second elements 104 or the measurement elements may have a shape of a square or a rectangle. In various embodiments, the plurality of second elements 104 may have a width of between about 30 mm to about 50 mm, a length of between about 30 mm to about 50 mm and a height of about 7 mm. However, it should be appreciated that the plurality of second elements 104 may have other sizes or shapes, for example the shape of a circle, a sphere, an oval or a polygon.

**[0084]** In the context of various embodiments, the plurality of second elements 104 or the measurement elements may emit ultrasonic beams with a central frequency (i.e. the second frequency) of above 500 kHz, for example in a range of between about 500 kHz to about 5 MHz (5000 kHz), for example a range of between about 500 kHz to about 3 MHz, a range of between about 500 kHz to about 1 MHz, a range of between about 1 MHz to about 5 MHz, a range of between about 1.6 MHz to about 5 MHz, or a range of between about 3 MHz to about 5 MHz, such that the ultrasonic beams may have a central frequency of about 500 kHz, about 700 kHz, about 800 kHz , about 1 MHz, about 1.6 MHz, about 3 MHz or about 5 MHz.

**[0085]** In various embodiments, the plurality of first elements 102 and the plurality of second elements 104 form part of an array of dual-frequency air-coupled ultrasonic transducers. In various embodiments, the array of ultrasonic transducers may be configured to perform calibration of the positions of the measurement elements (i.e. the plurality of second elements 104) and the actuation elements (i.e. the plurality of first elements 102) relative to the corneal surface. The calibration process may be performed prior to measurement of the IOP.

**[0086]** In various embodiments, as the array of ultrasonic transducers are air-coupled, the array of ultrasonic transducers utilise ambient air for the transmission of ultrasonic beams for performing measurements. As a result of the huge acoustic impedance mismatch between air and cornea, most of the acoustic or ultrasonic energy or signals incident on the corneal surface is reflected back from the corneal surface. This advantageously enable the measurement elements to sense or measure the corneal vibration velocity (i.e. the corneal surface velocity), the corneal structural impedance (i.e. the impedance of the corneal structure) and the curvature profile of the corneal surface, as the reflected acoustic signals carry the information for these parameters and are therefore used to determine these parameters.

**[0087]** However, the acoustic impedance mismatch between air and cornea results in poor penetration of the ultrasonic energy or signals into the corneal surface or structure. Therefore, signals that penetrate into the corneal surface are weak and become even weaker when the signals are reflected back to the measurement elements. Such weak signals may not be sufficient for the determination of the thickness profile of the corneal surface. However, various embodiments provide a method of determining the thickness profile based on frequency domain measurements, which overcome the issues related to the weak signals.

**[0088]** FIG. 2 shows a schematic block diagram of an ocular device 200, according to various embodiments. The ocular device 200 includes a non-contact ultrasonic device 202.

**[0089]** In the context of various embodiments, the ocular device 200 may include a tonometer, a lens, a spectacle glass or a goggle glass.

**[0090]** FIG. 3A shows a schematic block diagram of a non-contact ultrasonic system 300 for determining an intraocular pressure of an eye, according to various embodiments. The non-contact ultrasonic system 300 includes a non-contact ultrasonic device 302 and a control module 304 in electrical communication with the non-contact ultrasonic device 302, wherein the control module 304 is configured to determine the intraocular pressure.

**[0091]** FIG. 3B shows a schematic block diagram of a non-contact ultrasonic system 310 for determining an intraocular pressure of an eye, according to various embodiments. The non-contact ultrasonic system 310 includes an ocular device 312 including a non-contact ultrasonic device 314 and a control module 316 in electrical communication with the non-contact ultrasonic device 314, wherein the control module 316 is configured to determine the intraocular pressure.

**[0092]** In various embodiments, the control module 304, 316, may include a digital signal processor configured to process results obtained from the non-contact ultrasonic device 302, 314.

**[0093]** In the context of various embodiments, the control module 304, 316, is configured to perform at least one of controlling the non-contact ultrasonic device 302, 314, implementing a measurement process flow to the non-contact ultrasonic device 302, 314, implementing beam forming control to the non-contact ultrasonic device 302, 314, performing signal processing of results from the non-contact ultrasonic device 302, 314, and determining the intraocular pressure of the eye.

**[0094]** In the context of various embodiments, the control module 304, 316, may be configured to determine a plurality of resonant frequencies of the corneal surface at a plurality of points on the corneal surface. The control module 304, 316, may be further configured to determine the intraocular pressure of the eye based on the plurality of resonant frequencies.

**[0095]** The non-contact ultrasonic system 300, 310, may comprise a memory which is for example used in the processing carried out by the non-contact ultrasonic system 300, 310. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory). In various embodiments, the memory may be included in the control module 304, 316.

**[0096]** FIG. 4 shows a flow chart 400 illustrating a method of controlling a non-contact ultrasonic device, according to various embodiments.

**[0097]** At 402, a corneal surface of an eye is actuated. In various embodiments, actuating the corneal surface of the eye includes emitting a plurality of actuation ultrasonic beams onto the corneal surface of the eye. The plurality of actuation ultrasonic beams may have a frequency of above 100 kHz, for example in a range of between about 100 kHz to about

5 MHz (5000 kHz), for example a range of between about 100 kHz to about 3 MHz, a range of between about 100 kHz to about 1 MHz, a range of between about 100 kHz to about 500 kHz, a range of between about 500 kHz to about 5 MHz, a range of between about 500 kHz to about 3 MHz, a range of between about 500 kHz to about 1.6 MHz or a range of between about 1.6 MHz to about 5 MHz, such that the plurality of actuation ultrasonic beams may have a frequency of about 100 kHz, about 200 kHz, about 300 kHz, about 500 kHz, about 1 MHz, about 1.6 MHz, about 3 MHz or about 5 MHz.

**[0098]** At 404, a plurality of measurement ultrasonic beams are emitted on a point on the actuated corneal surface. The plurality of measurement ultrasonic beams may have a frequency of above 500 kHz, for example in a range of between about 500 kHz to about 5 MHz (5000 kHz), for example a range of between about 500 kHz to about 3 MHz, a range of between about 500 kHz to about 1 MHz, a range of between about 1 MHz to about 5 MHz, a range of between about 1.6 MHz to about 5 MHz, or a range of between about 3 MHz to about 5 MHz, such that the plurality of measurement ultrasonic beams may have a frequency of about 500 kHz, about 700 kHz, about 800 kHz , about 1 MHz, about 1.6 MHz, about 3 MHz or about 5 MHz..

**[0099]** At 406, a reflected ultrasonic beam is received from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface.

**[0100]** FIG. 5 shows a schematic block diagram of a non-contact ultrasonic system 500 for determining an intraocular pressure of an eye, according to various embodiments. The non-contact ultrasonic system 500 includes a topographic profile determination circuit 502 configured to determine a topographic profile of a corneal surface of the eye, a tensional force determination circuit 504 configured to determine a tensional force of the corneal surface, and an intraocular pressure determination circuit 506 configured to determine the intraocular pressure of the eye based on the tensional force and the topographic profile.

**[0101]** The non-contact ultrasonic system 500 may comprise a memory which is for example used in the processing carried out by the non-contact ultrasonic system 500. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM

(Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

**[0102]** FIG. 6 shows a flow chart 600 illustrating a method of determining an intraocular pressure of an eye, according to various embodiments.

**[0103]** At 602, a topographic profile of a corneal surface of the eye is determined.

**[0104]** At 604, a tensional force of the corneal surface is determined.

**[0105]** At 606, the intraocular pressure of the eye is determined based on the tensional force and the topographic profile.

**[0106]** In various embodiments, in order to determine the topographic profile of the corneal surface at 602, a plurality of first ultrasonic beams is emitted on a point on the corneal surface of the eye, and a reflected ultrasonic beam is received from the plurality of first ultrasonic beams reflected at the point on the corneal surface.

**[0107]** In various embodiments, the plurality of first ultrasonic beams are emitted from a first active group of the plurality of first elements and the reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the corneal surface is received with a first passive group of the plurality of first elements. The position of the first passive group is then determined. These processes may be repeated for a plurality of points on the corneal surface.

**[0108]** Subsequently, the plurality of first ultrasonic beams is emitted from a second or more active groups on the point on the corneal surface, and the reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the corneal surface is received with one or more passive groups of the plurality of first elements. The positions of the one or more passive groups are then determined.

**[0109]** Subsequently, the reflected ultrasonic beam is transformed into a frequency domain profile so as to determine a frequency difference between at least two peaks of at least two adjacent orders of frequency components of the reflected ultrasonic beam in the frequency domain profile.

**[0110]** In various embodiments, phase delays may be provided to at least one of the plurality of first ultrasonic beams to enable the wave fronts of the plurality of first ultrasonic beams to reach the corneal surface at least substantially simultaneously.

[0111] In various embodiments, in order to determine the tensional force of the corneal surface at 604, the corneal surface is actuated. The corneal surface of the eye may be actuated continuously.

[0112] In order to actuate the corneal surface, a plurality of second ultrasonic beams generating a first ultrasonic pressure, $P_1$, at the corneal surface is emitted from a first group of a plurality of second elements and a plurality of third ultrasonic beams generating a second ultrasonic pressure, $P_2$, at the corneal surface is emitted from a second group of the plurality of second elements.

[0113] In various embodiments, $P_1$ may be at least substantially equal to $P_0 \sin(2\pi f_0 t)$ where $P_0$ is a peak pressure, $f_0$ is a frequency of the plurality of second ultrasonic beams, and t is time.

[0114] In various embodiments, $P_2$ may be at least substantially equal to $P_0 \sin(2\pi(f_0 + 2f_1)t)$ where $P_0$ is a peak pressure, $(f_0 + 2f_1)$ is a frequency of the plurality of third ultrasonic beams, and t is time.

[0115] In various embodiments, the frequency $f_1$ may be varied.

[0116] Subsequently, a plurality of tone burst signals may be emitted at a plurality of positions on the actuated corneal surface, and a plurality of reflected tone burst signals are received from the plurality of tone burst signals reflected at the plurality of positions on the actuated corneal surface, and a frequency shift between the plurality of tone burst signals and the plurality of reflected tone burst signals at each of the plurality of positions is determined.

[0117] Subsequently, a corneal surface velocity corresponding to each of the plurality of positions on the corneal surface is determined, based on the frequency shift at each of the plurality of positions.

[0118] Subsequently, a resonant frequency of the corneal surface at each of the plurality of positions on the corneal surface is determined based on the corneal surface velocity, wherein the tensional force is a function of the corneal resonant frequency.

[0119] In further embodiments, in order to determine the tensional force of the corneal surface at 604, an impedance of the corneal surface is determined. In order to determine the impedance of the corneal surface, a reflectance of the corneal surface is determined.

[0120] In yet further embodiments, in order to determine the tensional force of the corneal surface at 604, a corneal resonant frequency is determined. In order to determine the corneal resonant frequency, a corneal surface velocity is determined.

[0121] FIG. 7 shows a schematic block diagram of a non-contact ultrasonic system 700 for determining an intraocular pressure of an eye, according to various embodiments. The non-contact ultrasonic system 700 includes a topographic profile determination circuit 702 configured to determine a topographic profile of a corneal surface of the eye, a plurality of first elements 704 configured to actuate the corneal surface, a plurality of second elements 706 configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface, and an intraocular pressure determination circuit 708 configured to determine the intraocular pressure of the eye based on the ultrasonic signal emitted, the reflected ultrasonic signal received and the topographic profile. In various embodiments, the plurality of second elements 706 may also be configured to actuate the corneal surface of an eye.

[0122] The non-contact ultrasonic system 700 may comprise a memory which is for example used in the processing carried out by the non-contact ultrasonic system 700. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

[0123] It should be appreciated that the descriptions relating to the plurality of first elements 102 and the plurality of second elements 104 of FIG. 1 may similarly be applicable respectively to the plurality of first elements 704 and to the plurality of second elements 706 of FIG. 7.

[0124] FIG. 8A shows a flow chart 800 illustrating a method of determining an intraocular pressure of an eye, according to various embodiments.

[0125] At 802, a topographic profile of a corneal surface of the eye is determined.

[0126] At 804, the corneal surface is actuated. In various embodiments, actuating the corneal surface includes emitting a plurality of actuation ultrasonic beams onto the corneal surface.

[0127] At 806, a plurality of measurement ultrasonic beams are emitted on a point on the actuated corneal surface.

[0128] At 808, a reflected ultrasonic beam is received from the plurality of measurement ultrasonic beams reflected at the point on the actuated corneal surface.

[0129] At 810, the intraocular pressure of the eye is determined based on the plurality of measurement ultrasonic beams emitted, the reflected ultrasonic beam received and the topographic profile.

[0130] FIG. 8B shows a flow chart 820 illustrating a method of determining an intraocular pressure of an eye, according to the embodiment of FIG. 8A. The flow chart 820 shows the processes that may be carried out at 810 of FIG. 8A.

[0131] At 822, a frequency shift between the plurality of measurement ultrasonic beams and the reflected ultrasonic beam is determined.

[0132] At 824, a corneal surface velocity is determined based on the frequency shift.

[0133] At 826, a resonant frequency of the corneal surface is determined based on the corneal surface velocity.

[0134] At 828, a tensional force of the corneal surface is determined based on the resonant frequency.

[0135] FIG. 9 shows a schematic block diagram of a non-contact ultrasonic system 900 for determining an information of an eye, according to various embodiments. The non-contact ultrasonic system 900 includes a plurality of elements 902 configured to emit a plurality of ultrasonic beams on a point on a corneal surface of the eye, and further configured to receive a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the corneal surface, and a control module 904 in electrical communication with the plurality of elements 902, wherein the control module 904 is configured to determine a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam to determine the information. In various embodiments, the information may include an intraocular pressure or a change in an intraocular pressure.

[0136] The non-contact ultrasonic system 900 may comprise a memory which is for example used in the processing carried out by the non-contact ultrasonic system 900. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory). In various embodiments, the memory may be included in the control module 904.

[0137] It should be appreciated that the descriptions relating to the plurality of second elements 104 of FIG. 1 may similarly be applicable to the plurality of elements 902 of FIG. 9 and the descriptions relating to the control module 304, 316 (FIGS. 3A, 3B) may similarly be applicable to the control module 904 of FIG. 9.

[0138] FIG. 10 shows a flow chart 1000 illustrating a method of determining an information of an eye, according to various embodiments. In various embodiments, the information may include an intraocular pressure or a change in an intraocular pressure.

[0139] At 1002, a plurality of ultrasonic beams are emitted on a point on a corneal surface of the eye.

[0140] At 1004, a reflected ultrasonic beam is received from the plurality of ultrasonic beams reflected at the point on the corneal surface.

[0141] At 1006, a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam is determined to determine the information.

[0142] In various embodiments, the processes at 1002, 1004 and 1006, may be repeated for a plurality of points on the corneal surface of the eye.

[0143] FIG. 11 shows a schematic block diagram of a non-contact ultrasonic system 1100 for determining a topographic profile of a deformable structure, according to various embodiments. The non-contact ultrasonic system 1100 includes a plurality of elements 1102 configured to emit a plurality of ultrasonic beams on a point on a surface of the deformable structure, and further configured to receive a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the surface, and a control module 1104 in electrical communication with the plurality of elements 1102, wherein the control module 1104 is configured to determine positions of the plurality of elements 1102 to determine the topographic profile.

**[0144]** In various embodiments, the plurality of elements 1102 includes an active group 1106 configured to emit the plurality of ultrasonic beams, and a passive group 1108 configured to receive the reflected ultrasonic beam.

**[0145]** The non-contact ultrasonic system 1100 may comprise a memory which is for example used in the processing carried out by the non-contact ultrasonic system 1100. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory). In various embodiments, the memory may be included in the control module 1104.

**[0146]** It should be appreciated that the descriptions relating to the plurality of second elements 104 of FIG. 1 may similarly be applicable to the plurality of elements 1102 of FIG. 11 and the descriptions relating to the control module control module 304, 316 (FIGS. 3A, 3B) may similarly be applicable to the control module 1104 of FIG. 11.

**[0147]** FIG. 12 shows a flow chart 1200 illustrating a method of determining a topographic profile of a deformable structure, according to various embodiments.

**[0148]** At 1202, a plurality of ultrasonic beams are emitted from a first active group of a plurality of elements on a point on a surface of the deformable structure.

**[0149]** At 1204, a reflected ultrasonic beam is received from the plurality of first ultrasonic beams reflected at the point on the surface with a first passive group of the plurality of elements.

**[0150]** At 1206, positions of the first active group and the first passive group are determined to determine the topographic profile.

**[0151]** In various embodiments, the processes at 1202, 1204 and 1206, may be repeated for a plurality of points on the surface of the deformable structure.

**[0152]** In various embodiments, the plurality of first ultrasonic beams may be emitted from a second or more active groups on the point on the surface of the deformable structure, and the reflected ultrasonic beam may be received from the plurality of first ultrasonic beams reflected at the point on the surface with one or more passive groups of the plurality of first elements. Subsequently, positions of the plurality of first elements in the one or more passive groups may be determined. These processes may be repeated for the plurality of points on the surface of the deformable structure.

**[0153]** Subsequently, each of the reflected ultrasonic beams may be transformed into a frequency domain profile for determining a frequency difference between at least two peaks of at least two adjacent orders of frequency components of each of the reflected ultrasonic beam in the frequency domain profile.

**[0154]** In various embodiments, a thickness of the deformable structure may be determined. The thickness may be determined from the equation $\Delta f = \frac{c}{2d}$ where d is the thickness of the deformable structure, c is a phase velocity of sound in the deformable structure and $\Delta f$ is a frequency difference between the at least two peaks of the at least two adjacent orders of frequency components.

**[0155]** FIG. 13 shows a schematic block diagram of a non-contact ultrasonic device 1300 for actuating a deformable structure, according to various embodiments. The non-contact ultrasonic device 1300 includes a plurality of first elements 1302 configured to emit a plurality of first ultrasonic beams having a first frequency at a surface of the deformable structure, and a plurality of second elements 1304 configured to emit a plurality of second ultrasonic beams having a second frequency at the surface of the deformable structure, wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency, and wherein the deformable structure is effectively actuated by a half of the third frequency.

**[0156]** Each of the plurality of first elements 1302 and each of the plurality of second elements 1304 have an at least substantially similar size or dimensions.

**[0157]** The plurality of first elements 1302 may be arranged in a first grid pattern and the plurality of second elements 1304 may be arranged in a second grid pattern, and the first grid pattern and the second grid pattern are spaced apart.

**[0158]** The plurality of first elements 1302 and the plurality of second elements 1304 are actuation elements and may be arranged spaced apart as in the embodiment of FIG. 15.

[0159] FIG. 14 shows a flow chart 1400 illustrating a method of actuating a deformable structure, according to various embodiments.

[0160] At 1402, a plurality of first ultrasonic beams having a first frequency is emitted for generating a first ultrasonic pressure, $P_1$, at a surface of the deformable structure.

[0161] At 1404, a plurality of second ultrasonic beams having a second frequency is emitted for generating a second ultrasonic pressure, $P_2$, at the surface of the deformable structure, wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency.

[0162] In the embodiment of FIG. 14, the deformable structure is effectively actuated by a half of the third frequency.

[0163] FIG. 15 shows a perspective view of a non-contact ultrasonic system 1500 comprising a non-contact ultrasonic device, as represented in the dotted box 1502, according to various embodiments. The non-contact ultrasonic device 1502 includes an array of dual-frequency air-coupled ultrasonic transducers, including ultrasonic measurement elements 1504 and ultrasonic actuation elements. In various embodiments, the actuation elements include upper actuation elements 1506a and lower actuation elements 1506b. In various embodiments, the measurement elements 1504 may also be configured as actuation elements.

[0164] The measurement elements 1504 include individual elements, for example as represented by 1508 for three such elements, the upper actuation elements 1506a include individual elements, for example as represented by 1510a for two such elements, and the lower actuation elements 1506b include individual elements, for example as represented by 1510b for two such elements.

[0165] In various embodiments, each individual actuation element, e.g. 1510a of the upper actuation elements 1506a and each individual actuation element e.g. 1510b of the lower actuation elements 1506b, are of a larger size than each individual measurement element e.g. 1508. However, it should be appreciated that each individual actuation element, e.g. 1510a of the upper actuation elements 1506a, each individual actuation element e.g. 1510b of the lower actuation elements 1506b and each individual measurement element e.g. 1508 may have at least substantially same size.

[0166] In various embodiments, the actuation elements (i.e. upper actuation elements 1506a and lower actuation elements 1506b) emit ultrasonic beams with relatively low ultrasonic frequencies while the measurement elements 1504 emit ultrasonic beams with relatively high ultrasonic frequencies. The actuation elements (i.e. upper actuation elements 1506a and lower actuation elements 1506b) may emit ultrasonic beams with a central frequency (e.g. first frequency) of above 100 kHz, for example in a range of between about 100 kHz to about 5 MHz (5000 kHz), for example a range of between about 100 kHz to about 3 MHz, a range of between about 100 kHz to about 1 MHz, a range of between about 100 kHz to about 500 kHz, a range of between about 500 kHz to about 5 MHz, a range of between about 500 kHz to about 3 MHz, a range of between about 500 kHz to about 1.6 MHz or a range of between about 1.6 MHz to about 5 MHz, such that the ultrasonic beams may have a central frequency of about 100 kHz, about 200 kHz, about 300 kHz, about 500 kHz, about 1 MHz, about 1.6 MHz, about 3 MHz or about 5 MHz. The measurement elements 1504 may emit ultrasonic beams with a central frequency (e.g. second frequency) of above 500 kHz, for example in a range of between about 500 kHz to about 5 MHz (5000 kHz), for example a range of between about 500 kHz to about 3 MHz, a range of between about 500 kHz to about 1 MHz, a range of between about 1 MHz to about 5 MHz, a range of between about 1.6 MHz to about 5 MHz, or a range of between about 3 MHz to about 5 MHz, such that the ultrasonic beams may have a central frequency of about 500 kHz, about 700 kHz, about 800 kHz , about 1 MHz, about 1.6 MHz, about 3 MHz or about 5 MHz.

[0167] The measurement elements 1504 are arranged in a grid pattern extending in a first direction (e.g. an azimuthal direction 1512) and a second direction (e.g. an elevation direction 1514), wherein the measurement elements 1504 are arranged with a number of the individual measurement element e.g. 1508 of the plurality of measurement elements 1504 in the azimuthal direction 1512 higher than in the elevation direction 1514. As shown in FIG. 15, the measurement elements 1504 are arranged in a grid pattern of 16 columns and 6 rows. Therefore, the number of individual measurement element e.g. 1508 in the azimuthal direction 1512 is 16 while the number of individual measurement element e.g. 1508 in the elevation direction 1514 is 6. However, it should be appreciated that the grid pattern may have a different number of columns and rows such that the number of individual measurement element e.g. 1508 of the measurement elements 1504 in the azimuthal direction 1512 and the elevation direction 1514 may be of a different number. For example, the number of individual measurement element e.g. 1508 in the azimuthal direction 1512 may be in a range of 10 to 30 or a range of 12 to 20 while the number of individual measurement element e.g. 1508 in the elevation direction 1514 may be in a range of 2 to 10 or a range of 4 to 8.

**[0168]** The upper actuation elements 1506a are arranged in a grid pattern extending in the azimuthal direction 1512 and the elevation direction 1514. As shown in FIG. 15, the number of individual actuation element e.g. 1510a of the upper actuation elements 1506a in the azimuthal direction 1512 is 10 while the number of individual actuation element e.g. 1510a in the elevation direction 1514 is 1. However, it should be appreciated that the number of individual actuation element e.g. 1510a of the upper actuation elements 1506a in the azimuthal direction 1512 and the elevation direction 1514 may be of a different number. For example, the number of individual actuation element e.g. 1510a in the azimuthal direction 1512 may be in a range of 4 to 10 while the number of individual actuation element e.g. 1510a in the elevation direction 1514 may be in a range of 1 to 3. In various embodiments, the description of the grid pattern of the upper actuation elements 1506a may be similarly applied to the lower actuation elements 1506b.

**[0169]** In various embodiments, as shown in FIG. 15, the upper actuation elements 1506a is arranged on one side of the grid pattern of the measurement elements 1504 in the elevation direction 1514 while the lower actuation elements 1506b is arranged on another side of the grid pattern of the measurement elements 1504 in the elevation direction 1514. Therefore, the upper actuation elements 1506a and the lower actuation elements 1506b are arranged on opposite sides with the measurement elements 1504 sandwiched in between, in the elevation direction 1514.

**[0170]** In various embodiments, providing the upper actuation elements 1506a, the lower actuation elements 1506b and the measurement elements 1504 in such an arrangement or configuration may relax the alignment requirements to the corneal center, thereby improving the robustness of the measurement.

**[0171]** It should be appreciated that the number of the individual measurement element, e.g. 1508 of the plurality of measurement elements 1504, may be different in each row and/or column of the grid pattern. This similarly applies to the grid patterns of the upper actuation elements 1506a and the lower actuation elements 1506b.

**[0172]** In addition, while FIG. 15 shows that the measurement elements 1504, the upper actuation elements 1506a and the lower actuation elements 1506b are arranged in grid patterns, it should be appreciated that the measurement elements 1504, the upper actuation elements 1506a and the lower actuation elements 1506b, may be arranged in any patterns or configurations extending in a first direction (e.g. an azimuthal direction 1512) and a second direction (e.g. an elevation direction 1514), where the number of the individual element e.g. 1508 of the plurality of measurement elements 1504, 1510a of the the upper actuation elements 1506a, and 1510b of the lower actuation elements 1506b, in the azimuthal direction 1512 is higher than in the elevation direction 1514.

**[0173]** As shown in FIG. 15, the non-contact ultrasonic device 1502 is bonded to a glass spectacle 1516 to form an ocular device 1518. Alternatively, the non-contact ultrasonic device 1502 may be bonded to a glass goggle.

**[0174]** In various embodiments, the non-contact ultrasonic device 1502 may be placed sufficiently closed to the eye 1520, at a distance of between about 1 cm to about 2 cm.

**[0175]** As shown in FIG. 15, the non-contact ultrasonic device 1502 or the ocular device 1518 is connected to or in electrical communication with a control module 1522, via a flexible cable ribbon 1524 for providing pathways for transmission of electrical signals between the control module 1522 and the non-contact ultrasonic device 1502. In various embodiments, the cable ribbon 1524 may be in electrical communication with the non-contact ultrasonic device 1502 via a connection socket (not shown) configured to connect or couple to a front-end integrated circuit (IC) of the non-contact ultrasonic device 1502.

**[0176]** In various embodiments, the control module 1522 is configured to perform at least one of controlling the non-contact ultrasonic device 1502, implementing a measurement process flow to the non-contact ultrasonic device 1502, implementing acoustic beam forming control to the non-contact ultrasonic device 1502, performing signal processing (e.g. digital signal processing) of results from the non-contact ultrasonic device 1502 and determining the intraocular pressure of the eye 1520. The control module 1522 may include a digital signal processor (not shown) configured to process the results or signals from the non-contact ultrasonic device 1502.

**[0177]** In various embodiments, the non-contact ultrasonic system 1500 may comprise a memory which is for example used in the processing carried out by the non-contact ultrasonic system 1500. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory). In various embodiments, the memory may be included in the control module 1522.

**[0178]** In various embodiments, the measurement of the intraocular pressure (IOP) may be achieved in a semi-continuous manner, i.e. measurements may be performed and readings of the IOP determined periodically or at a set of intervals. In various embodiments, each single IOP reading may take the steps as described below, with reference to FIGS. 15 to 17. However, it should be appreciated that one or more steps may be omitted, may be performed in addition to other steps or may be performed alternatively to other steps.

**[0179]** As an initial process, in various embodiments, the non-contact ultrasonic system 1500 may perform position calibration of the non-contact ultrasonic device 1502 relative to the eye 1520.

**[0180]** The non-contact ultrasonic system 1500 may then be configured to determine a topographic profile of a corneal surface of the eye 1520, using the measurement elements 1504.

**[0181]** FIGS. 16A to 16C show cross-sectional views of a method to determine a topographic profile of a corneal surface 1600 of an eye 1520, according to various embodiments.. As an example and not limitation, the method of determining the topographic profile of the corneal surface 1600 is first discussed with reference to the active group 1602 of the measurement elements 1504. When the elements in the active group 1602 are actuated electrically, they emit a plurality of ultrasonic beams 1604. In various embodiments, an element that is actuated to emit an ultrasonic beam may be referred to as an 'active element'.

[0182] The control module 1522 (FIG. 15) implements beam-forming control to the non-contact ultrasonic device 1502 and sets pre-determined phase delays to the elements of the active group 1602, to focus and steer the plurality of ultrasonic beams 1604 on a point 1606 on the corneal surface 1600 of the eye 1520. Therefore, the active elements of the active group 1602 emit and focus the plurality of ultrasonic beams 1604, with pre-determined phase delays, on the point 1606. The incident plurality of ultrasonic beams 1604 are effectively steered and focused to the point 1606 at a certain incident angle.

[0183] The plurality of ultrasonic beams 1604, incident at the point 1606 of the corneal surface 1600, are reflected at the point 1606 as a reflected ultrasonic beam 1608 along a certain path at a certain reflected angle, as shown in FIG. 16A. Due to the effect of the curvature of the corneal surface 1600 at the incident point 1606, the reflected ultrasonic beam 1608 is received or detected by an element in the passive group 1610 of the measurement elements 1504. The position of the active group 1602 and position of the passive group 1610 are determined and/or recorded. In various embodiments, an element that is not actuated to emit an ultrasonic beam may be referred to as a 'passive element'. Any passive element may receive a reflected ultrasonic beam.

[0184] Subsequently, as shown in FIG. 16B, the beam-forming control steers and focuses the plurality of ultrasonic beams 1604, with pre-determined phase delays, from the active group 1602, at a different incident angle on a point 1612 on the corneal surface 1600 of the eye 1520. The plurality of ultrasonic beams 1604, incident at the point 1612, are then reflected at the point 1612 as a reflected ultrasonic beam 1614 along a certain path at a certain reflected angle, different to those of the reflected ultrasonic beam 1608 (FIG. 16A). The reflected ultrasonic beam 1614 is received or detected by an element in a passive group 1616 of the measurement elements 1504. The position of the active group 1602 and the position of the passive group 1616 are determined and/or recorded.

[0185] The process of emitting and focusing the plurality of ultrasonic beams 1604 from the active group 1602, and determining the position of the active group 1602 and the position of the passive group that receives the reflected ultrasonic beam, may be repeated using the beam-forming control and steering to focus the plurality of ultrasonic beams 1604 at a plurality of points (i.e. at different points) at different incident angles on the corneal surface 1600 to scan the corneal surface 1600.

**[0186]** Subsequently, as shown in FIG. 16C, in a process of active element shifting, another active group 1618 may be actuated to emit and focus a plurality of ultrasonic beams 1620, with pre-determined phase delays, on the point 1622, at a certain incident angle, on the corneal surface 1600 of the eye 1520. The plurality of ultrasonic beams 1620, incident at the point 1622, are then reflected at the point 1622 as a reflected ultrasonic beam 1624 along a certain path at a certain reflected angle, and is received or detected by an element in a passive group 1626 of the measurement elements 1504. The position of the active group 1618 and the position of the passive group 1626 are determined and/or recorded.

**[0187]** The process of emitting and focusing the plurality of ultrasonic beams 1620 from the active group 1618, and determining the position of the active group 1618 and the position of the passive group that receives the reflected ultrasonic beam, may be repeated using the beam-forming control and steering to focus the plurality of ultrasonic beams 1620 at a plurality of points (i.e. at different points) at different incident angles on the corneal surface 1600 to scan the corneal surface 1600.

**[0188]** Subsequently, the process may be repeated using further active groups of the measurement elements 1504 to emit and focus a plurality of ultrasonic beams successively at a plurality of points on the corneal surface. As an example, the process may be repeated using any active groups of the measurement elements 1504 along the azimuthal direction 1512 (FIG. 15) and/or the elevation direction 1514 (FIG. 15) on any side of the corneal surface 1600 in order to map or determine the topographic profile of the corneal surface 1600. Therefore, at any one time, an active group of the measurement elements 1504 along any column and/or row of the grid pattern of the measurement elements 1504, may be activated to emit a plurality of ultrasonic beams. Further passive groups of the measurement elements 1504 may receive the ultrasonic beam reflected from the plurality of points on the corneal surface from the plurality of ultrasonic beams emitted by the further active groups of the measurement elements 1504.

**[0189]** While the scanning and shifting processes of the active elements may be performed in both the azimuthal direction 1512 (FIG. 15) and the elevation direction 1514 (FIG. 15), there is more freedom in the azimuthal direction 1512 (FIG. 15) due to the relatively higher number of individual element e.g. 1508 (FIG. 15) arranged in the azimuthal direction 1512 (FIG. 15) than in the elevation direction 1514 (FIG. 15).

**[0190]** As shown in FIGS. 16A to 16C, the active groups 1602, 1618, include four elements. However, it should be appreciated that the active groups 1602, 1618, may include different numbers of elements actuated to emit ultrasonic beams, e.g. two elements, three elements, five elements or any number of elements. In addition, as shown in FIGS. 16A to 16C, the passive groups 1610, 1616, 1626, include 1 element. However, it should be appreciated that the passive groups 1610, 1616, 1626, may include different numbers of elements, e.g. two elements, three elements or any number of elements, to receive the reflected ultrasonic beam.

**[0191]** For each measurement process, the incident angle, the reflected angle and the positions of the active group and the passive group may be determined and/or recorded. The topographic profile, for example the corneal curvature profile, of the corneal surface 1600 of the eye 1520 may be determined from the incident angles, and the corresponding positions of the active groups and the positions of the passive groups determined in all the measurements performed. In addition, the measurements determined may facilitate position calibrations of the array of ultrasonic transducers 1502 (FIG. 15).

**[0192]** In various embodiments, the reflected ultrasonic beam reflected at each incident point and received by a passive group of the measurement elements may be used to determine a thickness of the corneal surface at the incident point. Accordingly, the corneal thickness profile may be determined by considering the reflected ultrasonic beams reflected at the plurality of incident points.

**[0193]** FIG. 17 shows a cross-sectional view of a method to determine a thickness at an incident point 1700 of a corneal surface 1702 of an eye, according to various embodiments. In order to determine the thickness, a plurality of ultrasonic beams 1704 may be generated by a plurality of active elements of the measurement elements (not shown) and incident at the incident point 1700. As shown in FIG. 17, the plurality of ultrasonic beams 1704 encounter two medium interfaces or medium boundaries and three layers of transmission medium. For illustration and clarity purposes, the plurality of incident ultrasonic beams are represented as a single beam 1704 in FIG. 17.

**[0194]** It should be appreciated that the plurality of ultrasonic beams 1704 may be equivalent to the plurality of ultrasonic beams 1604 (FIGS. 16A and 16B) and the plurality of ultrasonic beams 1620 (FIG. 16C) such that the process of determining the corneal curvature profile and the corneal thickness profile of the corneal surface may be performed at least substantially simultaneously. For example, referring to FIG. 16A, while the incident angle of the plurality of ultrasonic beams 1604, and the positions of the active group 1602 and the passive group 1610 are determined and recorded, the process as illustrated in FIG. 17 simultaneously occur such that the plurality of ultrasonic beams 1604 (FIG. 16A) and the plurality of ultrasonic beams 1704 (FIG. 17) refer to the same ultrasonic beams.

**[0195]** As shown in FIG. 17, the plurality of ultrasonic beams 1704 encounter an interface 1706a between ambient air 1708 and the corneal surface 1702 and another interface 1706b between the corneal surface 1702 and the aqueous humor 1710. The interfaces 1706a, 1706b, form a reverberant chamber.

**[0196]** When the plurality of ultrasonic beams 1704 are incident at the point 1700, a majority of the ultrasonic or acoustic energy is reflected at the interface 1706a as a $1^{st}$-order reflected component or ultrasonic beam 1712a, while part of the ultrasonic energy is transmitted into the corneal surface 1702 as an ultrasonic beam 1714. The $1^{st}$-order reflected component 1712a is received by one or more passive elements of the measurement elements (not shown).

**[0197]** Subsequently, the ultrasonic beam 1714 is reflected and transmitted at every medium interface the ultrasonic beam 1714 encounters. As shown in FIG. 17, the ultrasonic beam 1714 is partly reflected at the interface 1706b as an ultrasonic beam 1716 towards the interface 1706a, and partly transmitted as an ultrasonic beam 1718 into the aqueous humor 1710.

**[0198]** The ultrasonic beam 1716 is then partly transmitted at the interface 1706a as a $2^{nd}$-order component or ultrasonic beam 1712b, and partly reflected at the interface 1706a as an ultrasonic beam 1720 towards the interface 1706b. The ultrasonic beam 1720 is then partly transmitted as an utrasonic beam 1722 at the interface 1706b and partly reflected at the interface 1706b as an ultrasonic beam 1724 towards the interface 1706a and subsequently partly transmitted at the interface 1706a as a 3rd-order component or ultrasonic beam 1712c. Each of the 2nd-order component 1712b and the 3rd-order component is received by one or more passive elements of the measurement elements (not shown).

**[0199]** In various embodiments, the process of reflection and transmission of ultrasonic beams at the interfaces 1706a, 1706b, may continue and an infinite number of components or ultrasonic beams may emerge from the interface 1706a, for example, a 4th-order component, a 5th-order component, a 6th-order component and any higher order number component.

**[0200]** The different orders of components, e.g. 1712a, 1712b, 1712c, form a signal with a fixed distance in the time domain.

**[0201]** In various embodiments, using the 1st-order component 1712a, the 2nd-order component 1712b and the 3rd-order component 1712c as an example and not limitation, any two adjacent order of components (e.g. the 1st-order reflected component 1712a and the 2nd-order reflected component 1712b, or the 2nd-order reflected component 1712b and the 3rd-order reflected component 1712c) has a frequency difference or frequency shift that may be determined from the equation:

$$\Delta f = \frac{c}{2d} \qquad \text{(Equation 1)},$$

where d is the thickness of the corneal surface 1702 at an incident point, e.g. 1700, and c is the phase velocity of sound in the corneal surface 1702.

**[0202]** In order to determine the corneal thickness, the different orders of components, e.g. 1712a, 1712b, 1712c, are transformed into the frequency domain to obtain a frequency domain profile of these components.

**[0203]** In the frequency domain profile, periodic sharp peaks are observed, corresponding to these components, and the distance between two adjacent peaks corresponding to two adjacent orders of components is $\Delta f$. Having determined $\Delta f$, the thickness, d, of the corneal surface 1702 at the incident point 1700 may be determined using equation 1. Therefore, the thickness profile of the corneal surface 1702 may be determined after the measurement elements (e.g. 1504 of FIGS. 15 and 16A-16C) have scanned the entire corneal surface 1702 and the thickness of the corneal surface 1702 determined at a plurality of incident points on the corneal surface 1702. Accordingly, the measurement elements (e.g. 1504 of FIGS. 15 and 16A-16C) of the array of ultrasonic transducers (e.g. 1502 of FIG. 15) may be configured to determine the corneal thickness profile through frequency domain analysis of the reflected acoustic waves at each incident point on the corneal surface 1702. In other words, each of the $1^{st}$-order reflected component or reflected ultrasonic beam 1712a and its associated higher order components (e.g. the $2^{nd}$-order component 1712b and the $3^{rd}$-order component 1712c) are transformed into a frequency domain profile so that a frequency difference between at least two peaks of at least two adjacent orders of frequency components of each of the reflected ultrasonic beam in the frequency domain profile may be determined, in order to determine the thickness of the corneal surface 1702 from equation 1.

**[0204]** Having determined the topographic profile (e.g. the corneal curvature profile and the corneal thickness profile) of the corneal surface, various embodiments may include the topographic profile of the corneal surface when determining the intraocular pressure (IOP).

**[0205]** In various embodiments, the methodology of intraocular pressure (IOP) measurement may be analogous to that of a rubber balloon filled with water. As the internal pressure increases, the tensional force increases. Therefore, an increased pressure of the aqueous humor (i.e. the IOP) inside the anterior chamber of a human eye causes an increased tensional force of the corneal surface. When the corneal thickness and curvature profiles have been determined, the IOP measurement is directly related to the corneal tensional force (i.e. the IOP is a function of the corneal tensional force).

**[0206]** In various embodiments, the corneal tensional force may be determined via two independent methods, based on ultrasonic sensing schemes.

**[0207]** In various embodiments, one method of determining the corneal tensional force is to monitor and determine the resonant frequency shift of the corneal surface or structure. The corneal surface may be akin to an elastic shell filled with liquid, such that its resonant frequencies may be related to the corneal elasticity, the topographic profile (e.g. the thickness and curvature profiles) of the cornea surface and the IOP. The relationship between the corneal resonance and the IOP may be determined, after having determined the topographic profile. According to various embodiments, the method of determining the corneal resonant frequencies utilise acoustic actuation and sensing methods to reach accurate measurements of the resonant frequencies.

**[0208]** In the context of various embodiments, the term 'corneal elasticity' may mean a linearised relationship between the strain and stress of the corneal surface or structure.

**[0209]** As the corneal surface has extremely low resonant frequencies, for example the first several modes are below 500 Hz, the conventional approaches use loudspeakers to actuate the human head proximal to the corneal surface. However, this results in the problems of low energy density and interferences involving other structural vibration modes.

**[0210]** In contrast, various embodiments use ultrasonic "beat" actuation technique to focus acoustic energy on the corneal surface, to achieve improved performance and measurement. In various embodiments, the actuation elements are configured to actuate the corneal surface, in order to measure the corneal resonant frequencies.

**[0211]** Referring to FIG. 15, the actuation elements include upper actuation elements 1506a and lower actuation elements 1506b. In various embodiments, the upper actuation elements 1506a generate and emit a plurality of ultrasonic beams at an ultrasonic frequency, $f_0$, thereby generating an ultrasonic pressure, $P_1$, at the corneal surface of the eye 1520. In various embodiments, the lower actuation elements 1506b generate and emit a plurality of ultrasonic beams at an ultrasonic frequency, $(f_0 + 2f_1)$, thereby generating an ultrasonic pressure, $P_2$, at the corneal surface of the eye 1520. The frequency $f_1$ is a low frequency and is lower than $f_0$.

**[0212]** In various embodiments, the ultrasonic beams emitted from elements, e.g. 1510a, in the central portion 1526a of the upper actuation elements 1506a are provided with certain pre-determined phase delays compared to the ultrasonic beams emitted by the elements, e.g. 1510a, in the outer portions 1526b, 1526c, to compensate for the planar surface of the array of ultrasonic transducers 1502 compared to the curved corneal surface of the eye 1520, so that the wave fronts of the ultrasonic beams emitted from all elements in the central portion 1526a and the outer portions 1526b, 1526c, of the upper actuation elements 1506a may reach the corneal surface at least substantially simultaneously. Similarly, the lower actuation elements 1506b may be configured such that the wave fronts of the ultrasonic beams emitted from all elements in the central portion 1526a and the outer portions 1526b, 1526c, of the lower actuation elements 1506b may reach the corneal surface at least substantially simultaneously.

**[0213]** It should be appreciated that the central portion 1526a may include any number of elements and correspondingly, the outer portions 1526b, 1526c may include any number of elements. Further, it should be appreciated that a different phase delay may be provided to each element, e.g. 1510a, in the central portion 1526a of the upper actuation elements 1506a and/or the lower actuation elements 1506b.

**[0214]** In various embodiments, the ultrasonic pressure $P_1$, generated by the plurality of ultrasonic beams at the ultrasonic frequency $f_0$ from the upper actuation elements 1506a, may be given by the following equation:

$$P_1 = P_0 \sin(2\pi f_0 t) \qquad \text{(Equation 2)},$$

where $P_0$ is the peak pressure and t is the time.

**[0215]** In various embodiments, the ultrasonic pressure $P_2$, generated by the plurality of ultrasonic beams at the ultrasonic frequency ($f_0$ + $2f_1$) from the lower actuation elements 1506b, may be given by the following equation:

$$P_2 = P_0 \sin(2\pi(f_0 + 2f_1)t) \qquad \text{(Equation 3)},$$

where $P_0$ is the peak pressure and t is the time, and where $2f_1$ is lower than $f_0$.

**[0216]** Subsequently, the effective pressure on the corneal surface may be determined from the following equation:

$$P_{eff} = 2P_0 \sin[(2\pi(f_0 + f_1)t)]\cos(2\pi f_1 t) \qquad \text{(Equation 4)}.$$

**[0217]** Accordingly, in various embodiments, the corneal surface is effectively actuated by an effective pressure at the low frequency, $f_1$ with a carrier frequency ($f_0$+$f_1$).

**[0218]** In various embodiments, the actuation process of the corneal surface is performed in a continuous way and may be performed independently from the measurement elements 1504. In addition, there is minimal acoustic interference between the ultrasonic beams emitted from the actuation elements (e.g. the upper actuation elements 1506a and the lower actuation elements 1506b), and the measurement elements 1504 as either $f_0$ or $2f_1$ is far below the operating frequency (e.g. above 500 kHz, for example in a range of between about 500 kHz to about 5 MHz (5000 kHz)) of the measurement elements 1504.

[0219] In order to determine the corneal resonant frequencies, the frequency $f_l$ is varied through a range of frequencies. When the desired vibration mode shapes are excited by sweeping $f_l$ through the range of frequencies in a certain interested region of the corneal surface, the corneal resonant frequencies may be determined through the 'Doppler effect'. In various embodiments, the corneal resonant frequency at an incident point on the corneal surface may be obtained by determining the corneal surface velocity at the incident point. In various embodiments, while the actuation elements continuously actuate the corneal surface, the measurement elements may be configured to sense or determine the corneal surface velocity through the 'Doppler effect'.

[0220] In various embodiments, the measurement elements 1504 may emit or send out tone burst signals (e.g. a plurality of ultrasonic beams) at a plurality of incident points on the corneal surface to scan the whole corneal surface. The signals reflected at each of the plurality of incident points exhibit a frequency shift (i.e. Doppler frequency shift) from the incident signals, where the frequency shift is directly related to the corneal surface velocity at a particular incident point. Therefore, the frequency shift is a function of the corneal surface velocity at the particular incident point. By detecting the magnitude of the frequency shift and retrieving the acoustic incident angle over the corneal surface based on the corneal curvature at the particular incident point on the corneal surface, the corneal surface velocity at the particular incident point may be determined.

[0221] In various embodiments, the corneal surface velocity V may be given by the following equation:

$$V = \frac{(\Delta f)c}{2f_0 \cos\theta} \qquad \text{(Equation 5)},$$

where $\Delta f$ is the Doppler frequency shift, c is the phase velocity of sound in the corneal surface, $f_0$ is the frequency of the plurality of ultrasonic beams generating the ultrasonic pressure $P_l$, and $\theta$ is the angle between the incident plurality of ultrasonic beams and the corneal surface velocity.

[0222] By using the array beam-forming control, the tone burst signals may be steered to a plurality of incident points on the corneal surface successively and the process of determining the corneal surface velocity is performed at each of the plurality of incident points. In this way, the corneal surface velocity is determined over the whole corneal surface and accordingly, the corneal resonant frequencies may be determined over the whole corneal surface, which advantageously would be more accurate according to experimental modal analysis theory. Experimental modal analysis refers to a subject that defines the methods for retrieving a structure's resonant frequencies and vibration mode shapes by observing the structure's responses. By using the experimental modal analysis, a set of methods or equations may be provided to determine the corneal resonant frequencies by determining the corneal velocity.

[0223] Subsequently, based on the corneal resonant frequencies and the topographic profile determined for the corneal surface, the corneal tensional force may be determined. An IOP reading may then be obtained, as the IOP is related to the corneal tensional force.

[0224] In various embodiments, the relationship between the corneal tensional force T, along the corneal surface or structure, and the corneal fundamental resonant frequency $\omega_0$ may be given by the following equation:

$$\omega_0 = \left(\frac{\alpha}{R}\right)\sqrt{\left(\frac{E}{\rho}\right)} + \eta\sqrt{\left(\frac{T}{\rho h}\right)\left(\frac{\pi}{R}\right)^2} \qquad \text{(Equation 6)},$$

where R is the corneal radius of curvature, E is the corneal structural elasticity, $\rho$ is the corneal density, h is the corneal thickness, and $\alpha$ and $\eta$ are geometrical factors. $\alpha$ and $\eta$ may be used, for example as correction factors in corneal modelling.

[0225] In various embodiments, the relationship between the intraocular pressure (IOP), P, and the corneal tensional force, T, may be given by the following equation:

$$T = \beta\left(\frac{PR}{2h}\right) \qquad \text{(Equation 7)},$$

where R is the corneal radius of curvature, h is the corneal thickness and $\beta$ is a geometrical factor. $\beta$ may be used, for example as a correction factor in corneal modelling.

[0226] In various embodiments, another method of determining the corneal tensional force is to monitor and determine the amplitudes of the ultrasonic beams reflected from the corneal surface or structure. It is known that a variation in IOP results in changes to the corneal structural tensional force. An increased IOP results in an increase in the corneal tensional force that is generated. As the corneal tensional force increases, the corneal surface becomes firmer. When ultrasonic or acoustic beams or waves are incident on the corneal surface, more acoustic energy are reflected from the corneal surface. Therefore, by monitoring the amplitudes of the reflected ultrasonic beams, the IOP may be determined. This approach also allows any fluctuation in the IOP to be determined by by monitoring or analyzing any variations or changes in the amplitudes of the reflected ultrasonic beams from the corneal surface, for example monitoring the amplitudes over time to detect any variations in the amplitudes. However, determining an absolute reading of the IOP may be challenging by using this approach solely. In addition, measurements obtained by determining the variations in the amplitudes may be susceptible to noise.

**[0227]** Based on this method, as an example and not limitation, the amplitude of an ultrasonic beam incident on the corneal surface is determined. In addition, the amplitude of an ultrasonic beam reflected from the corneal surface from this incident ultrasonic beam is determined. A reflectance of the corneal surface may then be determined by determining a ratio of the amplitude of the reflected ultrasonic beam to the amplitude of the incident ultrasonic beam.

**[0228]** Subsequently, an impedance of the corneal surface may be determined where the relationship between the impedance, z, and the reflectance, R, of the corneal surface may be given by the following equations:

$$R = \frac{\xi\cos\theta - 1}{\xi\cos\theta + 1} \qquad \text{(Equation 8),}$$

$$\xi = \frac{z}{\rho c} \qquad \text{(Equation 9),}$$

where ρ is the corneal density, c is the phase velocity of sound in the corneal surface and θ is the incident angle of the incident ultrasonic beam. In various embodiments, a higher tensional force results in a higher impedance.

**[0229]** In order to determine a fluctuation in the IOP, the amplitude of the reflected ultrasonic beam may be determined. Any changes in the amplitude of the reflected ultrasonic beam results in a change in the reflectance, R, and hence the impedance, z, of the corneal surface. Correspondingly, the change in the impedance leads to a change in the tensional force and therefore the intraocular pressure.

[0230] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

## CLAIMS

1. A non-contact ultrasonic device, comprising:

a plurality of first elements configured to actuate a corneal surface of an eye; and

a plurality of second elements configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface.

2. The non-contact ultrasonic device as claimed in claim 1, wherein the plurality of first elements are configured to emit a plurality of actuation ultrasonic beams to actuate the corneal surface.

3. The non-contact ultrasonic device as claimed in claim 2, wherein the plurality of actuation ultrasonic beams have a first frequency and the plurality of measurement ultrasonic beams have a second frequency, wherein the second frequency is higher than the first frequency.

4. The non-contact ultrasonic device as claimed in claim 3, wherein the first frequency is above 100 kHz.

5. The non-contact ultrasonic device as claimed in claim 3 or 4, wherein the second frequency is above 500 kHz.

6. The non-contact ultrasonic device as claimed in any one of claims 1 to 5, wherein each of the plurality of first elements have a first size and each of the plurality of second elements have a second size.

7. The non-contact ultrasonic device as claimed in any one of claims 1 to 6, wherein the plurality of second elements are arranged in a first grid pattern extending in a first direction and a second direction, wherein a number of the plurality of second elements in the first direction is higher than in the second direction.

8. The non-contact ultrasonic device as claimed in claim 7, wherein the plurality of first elements are arranged in a second grid pattern on a first side and a second side of the first grid pattern of the plurality of second elements in the second direction.

9. An ocular device comprising a non-contact ultrasonic device as claimed in any one of claims 1 to 8.

10. The ocular device as claimed in claim 9, wherein the ocular device comprises a tonometer, a lens, a spectacle glass or a goggle glass.

11. A non-contact ultrasonic system for determining an intraocular pressure of an eye, comprising:

a non-contact ultrasonic device as claimed in any one of claims 1 to 8 or an ocular device comprising a non-contact ultrasonic device as claimed in claim 9 or 10; and

a control module in electrical communication with the non-contact ultrasonic device, wherein the control module is configured to determine the intraocular pressure.

12. The non-contact ultrasonic system as claimed in claim 11, wherein the control module comprises a digital signal processor configured to process results obtained from the non-contact ultrasonic device.

13. The non-contact ultrasonic system as claimed in claim 11 or 12, wherein the control module is configured to perform at least one of controlling the non-contact ultrasonic device, implementing a measurement process flow to the non-contact ultrasonic device, implementing beam forming control to the non-contact ultrasonic device, performing signal processing of results from the non-contact ultrasonic device and determining the intraocular pressure of the eye.

14. The non-contact ultrasonic system as claimed in any one of claims 11 to 13, wherein the control module is configured to determine a plurality of resonant frequencies of the corneal surface at a plurality of points on the corneal surface.

15. The non-contact ultrasonic system as claimed in claim 14, wherein the control module is further configured to determine the intraocular pressure of the eye based on the plurality of resonant frequencies.

16. A method of controlling a non-contact ultrasonic device, comprising:

actuating a corneal surface of an eye;

emitting a plurality of measurement ultrasonic beams on a point on the actuated corneal surface; and

receiving a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface.

17. The method as claimed in claim 16, wherein actuating the corneal surface of the eye comprises emitting a plurality of actuation ultrasonic beams onto the corneal surface.

18. The method as claimed in claim 17, wherein the plurality of actuation ultrasonic beams have a frequency of above 100 kHz.

19. The method as claimed in any one of claims 16 to 18, wherein the plurality of measurement ultrasonic beams have a frequency of above 500 kHz.

20. A non-contact ultrasonic system for determining an intraocular pressure of an eye, comprising:

a topographic profile determination circuit configured to determine a topographic profile of a corneal surface of the eye;

a tensional force determination circuit configured to determine a tensional force of the corneal surface; and an intraocular pressure determination circuit configured to determine the intraocular pressure of the eye based on the tensional force and the topographic profile.

21. A method of determining an intraocular pressure of an eye, comprising:

determining a topographic profile of a corneal surface of the eye;

determining a tensional force of the corneal surface; and

determining the intraocular pressure of the eye based on the tensional force and the topographic profile.

22. The method as claimed in claim 21, wherein determining the topographic profile of the corneal surface comprises:

emitting a plurality of first ultrasonic beams on a point on the corneal surface of the eye; and

receiving a reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the corneal surface.

23. The method as claimed in claim 22, wherein emitting the plurality of first ultrasonic beams comprises emitting the plurality of first ultrasonic beams from a first active group of a plurality of first elements, and wherein receiving the reflected ultrasonic beam comprises receiving the reflected ultrasonic beam with a first passive group of the plurality of first elements.

24. The method as claimed in claim 23, further comprising determining the position of the first passive group.

25. The method as claimed in claim 24, wherein the method is repeated for a plurality of points on the corneal surface.

26. The method as claimed in claim 25, wherein determining the topographic profile of the corneal surface further comprises:

emitting the plurality of first ultrasonic beams from a second or more active groups on the point on the corneal surface; and

receiving the reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the corneal surface with one or more passive groups of the plurality of first elements.

27. The method as claimed in claim 26, further comprising determining positions of the one or more passive groups.

28. The method as claimed in any one of claims 22 to 27, further comprising performing a transformation of the reflected ultrasonic beam into a frequency domain profile to determine a frequency difference between at least two peaks of at least two adjacent orders of frequency components of the reflected ultrasonic beam in the frequency domain profile.

29. The method as claimed in any one of claims 22 to 28, wherein emitting the plurality of first ultrasonic beams on the point on the corneal surface comprises providing phase delays to at least one of the plurality of first ultrasonic beams.

30. The method as claimed in any one of claims 21 to 29, wherein the topographic profile comprises at least one of a curvature profile and a thickness profile.

31. The method as claimed in any one of claims 21 to 30, wherein determining the tensional force of the corneal surface comprises actuating the corneal surface.

32. The method as claimed in claim 31, wherein actuating the corneal surface of the eye comprises emitting a plurality of second ultrasonic beams generating a first ultrasonic pressure, $P_1$, at the corneal surface from a first group of a plurality of second elements.

33. The method as claimed in claim 32, wherein the first ultrasonic pressure, $P_1$, is determined from the following equation:

$$P_1 = P_0 \sin(2\pi f_0 t)$$

where

$P_0$ is a peak pressure,

$f_0$ is a frequency of the plurality of second ultrasonic beams, and

t is a time.

34. The method as claimed in claim 32 or 33, wherein actuating the corneal surface of the eye further comprises emitting a plurality of third ultrasonic beams generating a second ultrasonic pressure, $P_2$, at the corneal surface from a second group of the plurality of second elements.

35. The method as claimed in claim 34, wherein the second ultrasonic pressure, $P_2$, is determined from the following equation:

$$P_2 = P_0 \sin(2\pi(f_0 + 2f_1)t)$$

where

$P_0$ is a peak pressure,

$(f_0 + 2f_1)$ is a frequency of the plurality of third ultrasonic beams, and

t is a time.

36. The method as claimed in claim 35, further comprising varying $f_1$.

37. The method as claimed in claim 36, further comprising:

emitting a plurality of tone burst signals at a plurality of positions on the actuated corneal surface;

receiving a plurality of reflected tone burst signals from the plurality of tone burst signals reflected at the plurality of positions on the actuated corneal surface; and

determining a frequency shift between the plurality of tone burst signals and the plurality of reflected tone burst signals at each of the plurality of positions.

38. The method as claimed in claim 37, further comprising determining a corneal surface velocity corresponding to each of the plurality of positions on the corneal surface, based on the frequency shift at each of the plurality of positions.

39. The method as claimed in claim 38, further comprising determining a resonant frequency of the corneal surface at each of the plurality of positions on the corneal surface based on the corneal surface velocity, and wherein the tensional force is a function of the corneal resonant frequency.

40. The method as claimed in any one of claims 31 to 39, comprising actuating the corneal surface of the eye continuously.

41. The method as claimed in any one of claims 21 to 30, wherein determining the tensional force of the corneal surface comprises determining an impedance of the corneal surface.

42. The method as claimed in claim 21, wherein determining the tensional force of the corneal surface comprises determining a corneal resonant frequency.

43. The method as claimed in claim 42, wherein determining the corneal resonant frequency comprises determining a corneal surface velocity.

44. The method as claimed in claim 42 or 43, wherein the topographic profile comprises at least one of a curvature profile and a thickness profile.

45. A non-contact ultrasonic system for determining an intraocular pressure of an eye, comprising:

a topographic profile determination circuit configured to determine a topographic profile of a corneal surface of the eye;

a plurality of first elements configured to actuate the corneal surface;

a plurality of second elements configured to emit a plurality of measurement ultrasonic beams on a point on the actuated corneal surface, and further configured to receive a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface; and

an intraocular pressure determination circuit configured to determine the intraocular pressure of the eye based on the plurality of measurement ultrasonic beams emitted, the reflected ultrasonic beam received and the topographic profile.

46. The non-contact ultrasonic system as claimed in claim 45, wherein the plurality of first elements are configured to emit a plurality of actuation ultrasonic beams to actuate the corneal surface.

47. The non-contact ultrasonic system as claimed in claim 46, wherein the plurality of actuation ultrasonic beams have a first frequency and the plurality of measurement ultrasonic beams have a second frequency, wherein the second frequency is higher than the first frequency.

48. The non-contact ultrasonic system as claimed in claim 47, wherein the first frequency is above 100 kHz.

49. The non-contact ultrasonic system as claimed in claim 47 or 48, wherein the second frequency is above 500 kHz.

50. The non-contact ultrasonic system as claimed in any one of claims 45 to 49, wherein each of the plurality of first elements have a first size and each of the plurality of second elements have a second size.

51. The non-contact ultrasonic system as claimed in any one of claims 45 to 50, wherein the plurality of second elements are arranged in a first grid pattern extending in a first direction and a second direction, wherein a number of the plurality of second elements in the first direction is higher than in the second direction.

52. The non-contact ultrasonic system as claimed in claim 51, wherein the plurality of first elements are arranged in a second grid pattern on a first side and a second side of the first grid pattern of the plurality of second elements in the second direction.

53. A method of determining an intraocular pressure of an eye, comprising:

determining a topographic profile of a corneal surface of the eye;

actuating the corneal surface;

emitting a plurality of measurement ultrasonic beams on a point on the actuated corneal surface;

receiving a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the actuated corneal surface; and

determining the intraocular pressure of the eye based on the plurality of measurement ultrasonic beams emitted, the reflected ultrasonic beam received and the topographic profile.

54. The method as claimed in claim 53, wherein actuating the corneal surface comprises emitting a plurality of actuation ultrasonic beams onto the corneal surface.

55. The method as claimed in claim 53 or 54, wherein determining the intraocular pressure of the eye comprises determining a frequency shift between the plurality of measurement ultrasonic beams and the reflected ultrasonic beam.

56. The method as claimed in claim 55, wherein determining the intraocular pressure of the eye further comprises determining a corneal surface velocity based on the frequency shift.

57. The method as claimed in claim 56, wherein determining the intraocular pressure of the eye further comprises determining a resonant frequency of the corneal surface based on the corneal surface velocity.

58. The method as claimed in claim 57, wherein determining the intraocular pressure of the eye further comprises determining a tensional force of the corneal surface based on the resonant frequency.

59. The method as claimed in any one of claims 54 to 58, wherein the topographic profile comprises at least one of a curvature profile and a thickness profile.

60. A non-contact ultrasonic system for determining an information of an eye, comprising:

a plurality of elements configured to emit a plurality of ultrasonic beams on a point on a corneal surface of the eye, and further configured to receive a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the corneal surface; and

a control module in electrical communication with the plurality of elements, wherein the control module is configured to determine a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam to determine the information.

61. The non-contact ultrasonic device as claimed in 60, wherein the plurality of elements are arranged in a grid pattern extending in a first direction and a second direction, wherein a number of the plurality of elements in the first direction is higher than in the second direction.

62. The non-contact ultrasonic device as claimed in claim 60 or 61, wherein the plurality of ultrasonic beams have a frequency of above 500 kHz.

63. The non-contact ultrasonic system as claimed in any one of claims 60 to 62, wherein the control module comprises a digital signal processor.

64. The non-contact ultrasonic device as claimed in any one of claims 60 to 63, wherein the information is an intraocular pressure or a change in an intraocular pressure.

65. A method of determining an information of an eye, comprising:

emitting a plurality of ultrasonic beams on a point on a corneal surface of the eye;

receiving a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the corneal surface; and

determining a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam to determine the information.

66. The method as claimed in claim 65, wherein the method is repeated for a plurality of points on the corneal surface of the eye.

67. The method as claimed in claim 65 or 66, wherein the information is an intraocular pressure or a change in an intraocular pressure.

68. A non-contact ultrasonic system for determining a topographic profile of a deformable structure, comprising:

a plurality of elements configured to emit a plurality of ultrasonic beams on a point on a surface of the deformable structure, and further configured to receive a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the surface; and

a control module in electrical communication with the plurality of elements, wherein the control module is configured to determine positions of the plurality of elements to determine the topographic profile.

69. The non-contact ultrasonic system as claimed in claim 68, wherein the plurality of elements comprise:

an active group configured to emit the plurality of ultrasonic beams; and

a passive group configured to receive the reflected ultrasonic beam.

70. The non-contact ultrasonic system as claimed in 68 or 69, wherein the plurality of elements are arranged in a grid pattern extending in a first direction and a second

direction, wherein a number of the plurality of elements in the first direction is higher than in the second direction.

71. The non-contact ultrasonic system as claimed in any one of claims 68 to 70, wherein the plurality of ultrasonic beams have a frequency of above 500 kHz.

72. The non-contact ultrasonic system as claimed in any one of claims 68 to 71, wherein the control module comprises a digital signal processor.

73. The non-contact ultrasonic system as claimed in any one of claims 68 to 72, wherein the deformable structure is a membrane or a corneal surface of an eye.

74. A method of determining a topographic profile of a deformable structure, comprising:

emitting a plurality of ultrasonic beams from a first active group of a plurality of elements on a point on a surface of the deformable structure;

receiving a reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the surface with a first passive group of the plurality of elements; and

determining positions of the first active group and the first passive group to determine the topographic profile.

75. The method as claimed in claim 74, wherein the method is repeated for a plurality of points on the surface of the deformable structure.

76. The method as claimed in claim 75, further comprising:

emitting the plurality of first ultrasonic beams from a second or more active groups on the point on the surface of the deformable structure; and

receiving the reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the surface with one or more passive groups of the plurality of first elements.

77. The method as claimed in claim 76, further comprising determining positions of the plurality of first elements in the one or more passive groups.

78. The method as claimed in claim 77, wherein the method is repeated for the plurality of points on the surface of the deformable structure.

79. The method as claimed in claim 78, further comprising performing a transformation of each of the reflected ultrasonic beams into a frequency domain profile to determine a frequency difference between at least two peaks of at least two adjacent orders of frequency components of each of the reflected ultrasonic beam in the frequency domain profile.

80. The method as claimed in claim 79, further comprising determining a thickness of the deformable structure from the following equation:

$$\Delta f = \frac{c}{2d}$$

where

d is a thickness of the deformable structure,

c is a phase velocity of sound in the deformable structure, and

$\Delta f$ is a frequency difference between the at least two peaks of the at least two adjacent orders of frequency components.

81. The method as claimed in any one of claims 73 to 80, wherein the deformable structure is a membrane or a corneal surface of an eye.

82. A non-contact ultrasonic device for actuating a deformable structure, comprising:

a plurality of first elements configured to emit a plurality of first ultrasonic beams having a first frequency at a surface of the deformable structure; and

a plurality of second elements configured to emit a plurality of second ultrasonic beams having a second frequency at the surface of the deformable structure, wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency, and wherein the deformable structure is effectively actuated by a half of the third frequency.

83. The non-contact ultrasonic device as claimed in claim 82, wherein each of the plurality of first elements and each of the plurality of second elements have an at least substantially similar size.

84. The non-contact ultrasonic device as claimed in claim 82 or 83, wherein the plurality of first elements are arranged in a first grid pattern and the plurality of second elements are arranged in a second grid pattern, and wherein the first grid pattern and the second grid pattern are spaced apart.

85. The non-contact ultrasonic device as claimed in any one of claims 82 to 84, wherein the deformable structure is a membrane or a corneal surface of an eye.

86. A method of actuating a deformable structure, comprising:

emitting a plurality of first ultrasonic beams having a first frequency for generating a first ultrasonic pressure, $P_1$, at a surface of the deformable structure; and

emitting a plurality of second ultrasonic beams having a second frequency for generating a second ultrasonic pressure, $P_2$, at the surface of the deformable structure,

wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency.

87. The method as claimed in claim 86, wherein the deformable structure is effectively actuated by a half of the third frequency.

88. The method as claimed in claim 86 or 87, wherein the deformable structure is a membrane or a corneal surface of an eye.

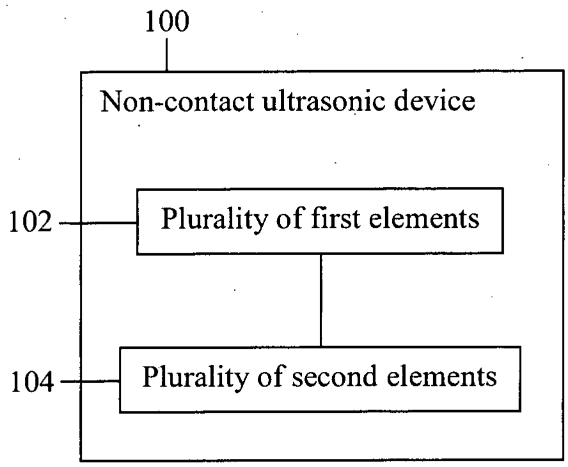
100
Non-contact ultrasonic device
102
Plurality of first elements
104
Plurality of second elements

FIG. 1

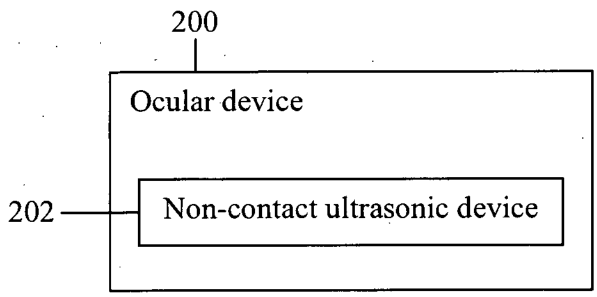
200
Ocular device
202
Non-contact ultrasonic device

FIG. 2

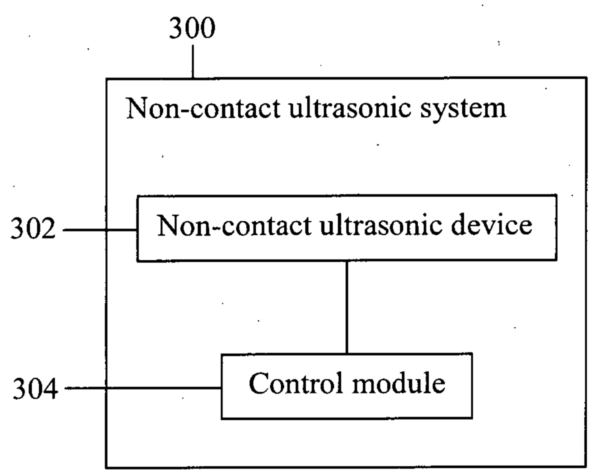
300
Non-contact ultrasonic system
302
Non-contact ultrasonic device
304
Control module

FIG. 3A

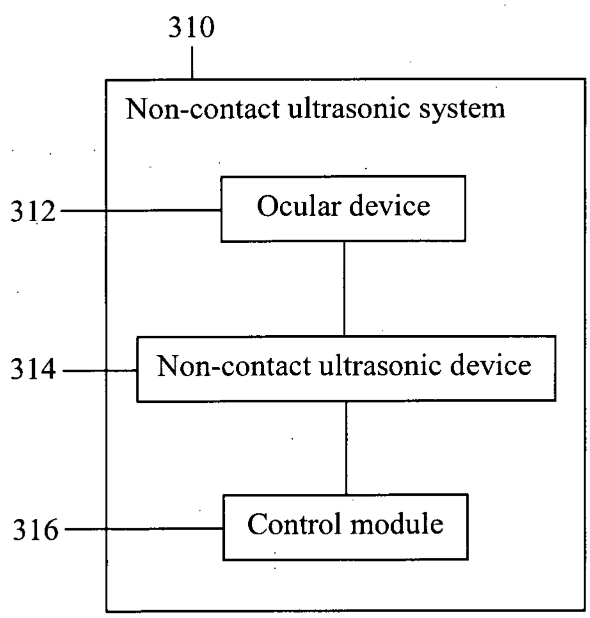
310
Non-contact ultrasonic system
312
Ocular device
314
Non-contact ultrasonic device
316
Control module

FIG. 3B

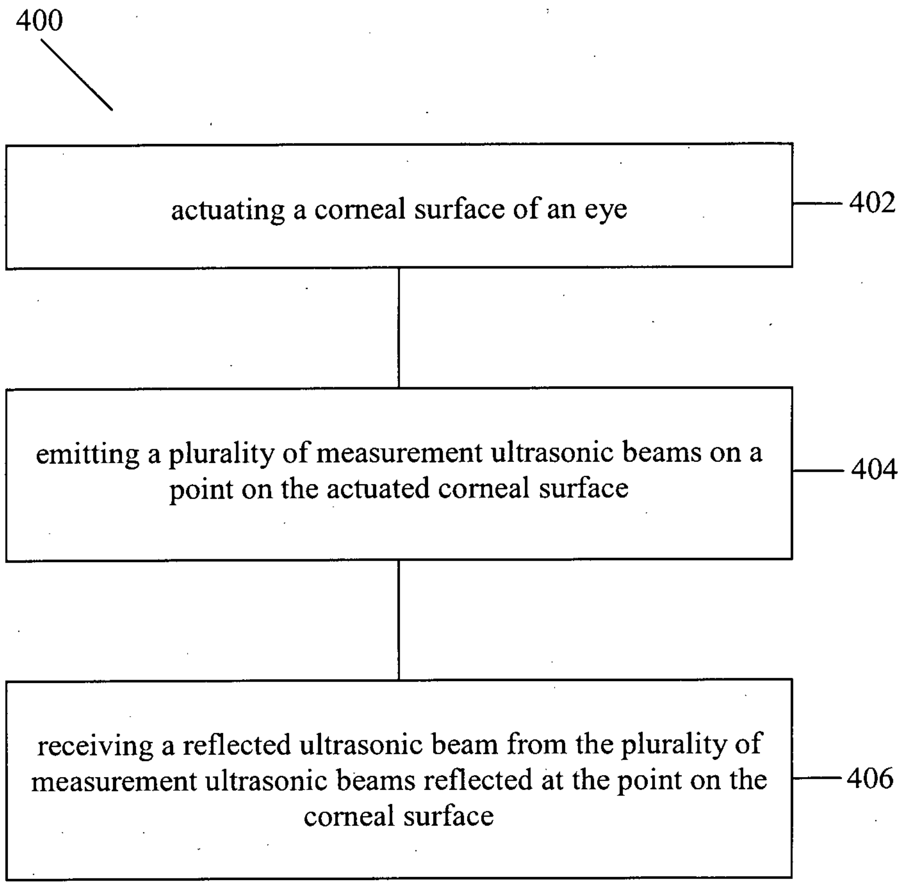
400
actuating a corneal surface of an eye
402
emitting a plurality of measurement ultrasonic beams on a point on the actuated corneal surface
404
receiving a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the corneal surface
406

FIG. 4

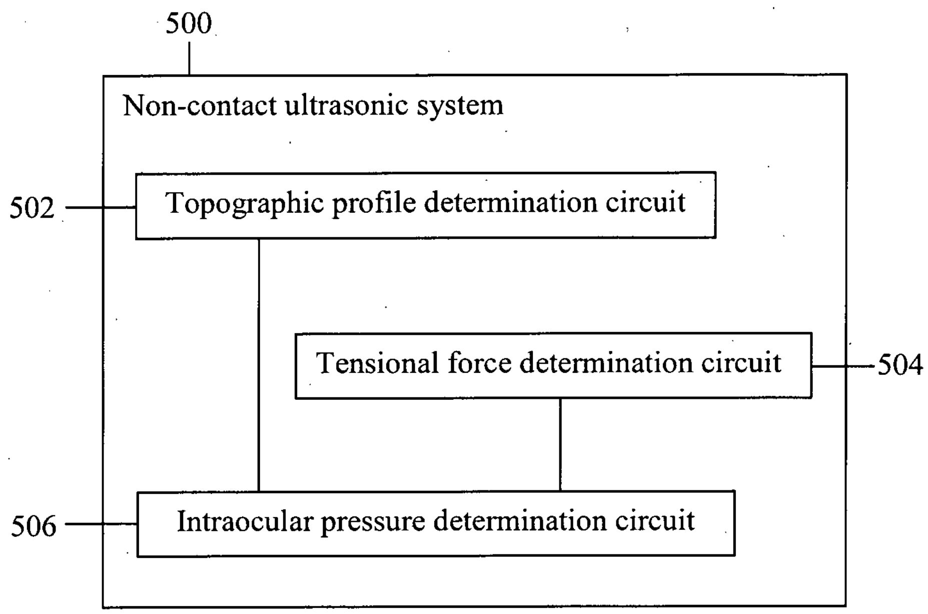
500
Non-contact ultrasonic system
502
Topographic profile determination circuit
Tensional force determination circuit
504
506
Intraocular pressure determination circuit

FIG. 5

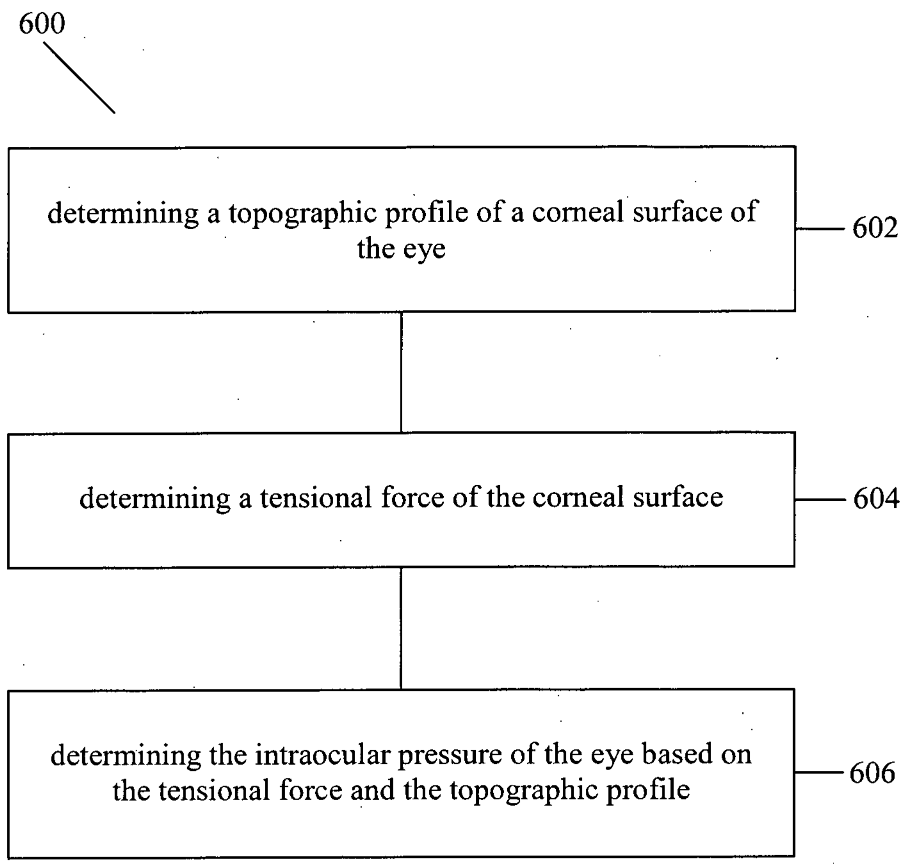
600
determining a topographic profile of a corneal surface of the eye
602
determining a tensional force of the corneal surface
604
determining the intraocular pressure of the eye based on the tensional force and the topographic profile
606

FIG. 6

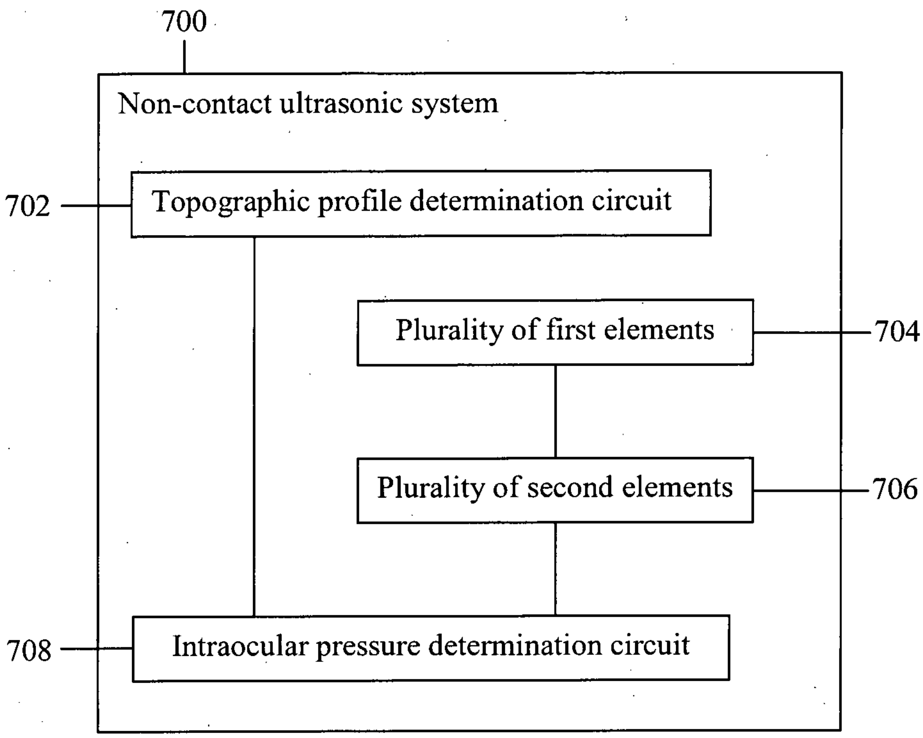
700
Non-contact ultrasonic system
702
Topographic profile determination circuit
Plurality of first elements
704
Plurality of second elements
706
708
Intraocular pressure determination circuit

FIG. 7

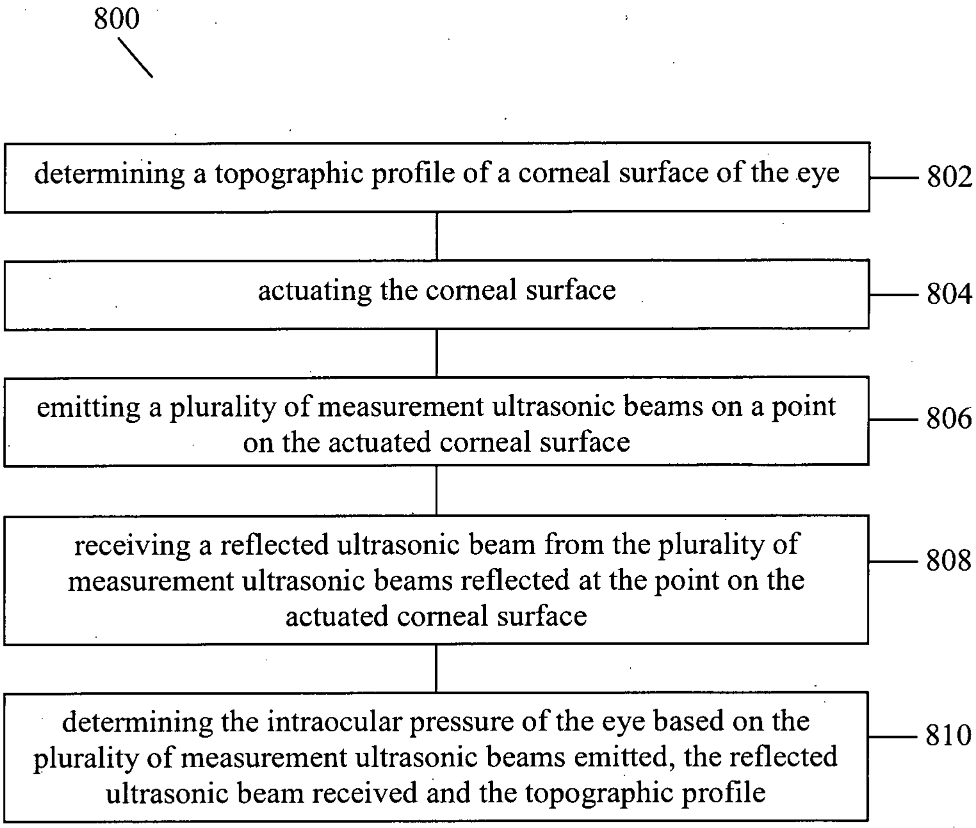
800
determining a topographic profile of a corneal surface of the eye
802
actuating the corneal surface
804
emitting a plurality of measurement ultrasonic beams on a point on the actuated corneal surface
806
receiving a reflected ultrasonic beam from the plurality of measurement ultrasonic beams reflected at the point on the actuated corneal surface
808
determining the intraocular pressure of the eye based on the plurality of measurement ultrasonic beams emitted, the reflected ultrasonic beam received and the topographic profile
810

FIG. 8A

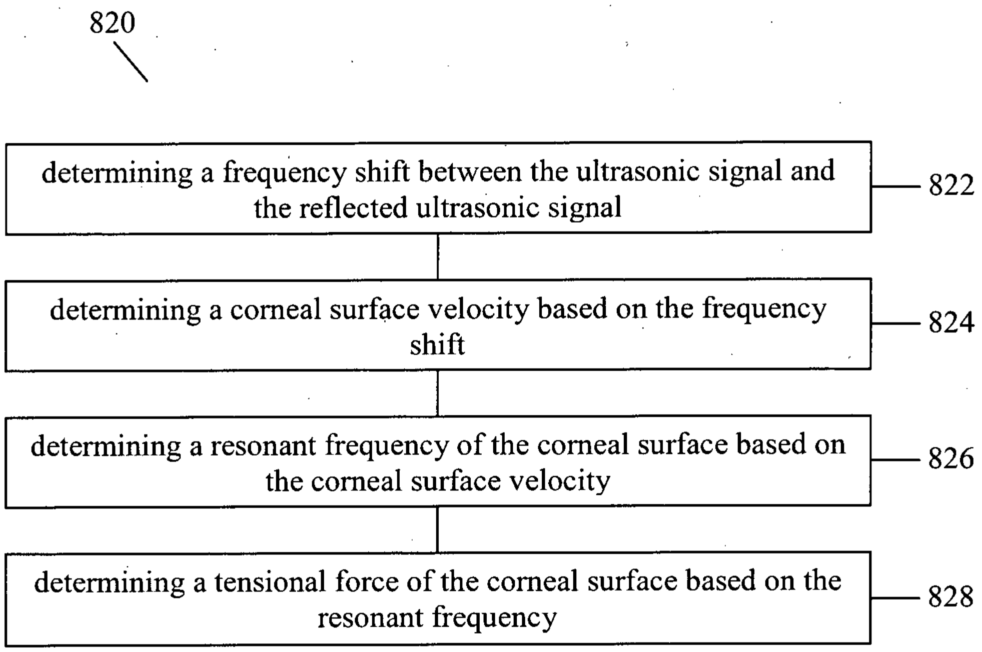
820
determining a frequency shift between the ultrasonic signal and the reflected ultrasonic signal
822
determining a corneal surface velocity based on the frequency shift
824
determining a resonant frequency of the corneal surface based on the corneal surface velocity
826
determining a tensional force of the corneal surface based on the resonant frequency
828

FIG. 8B

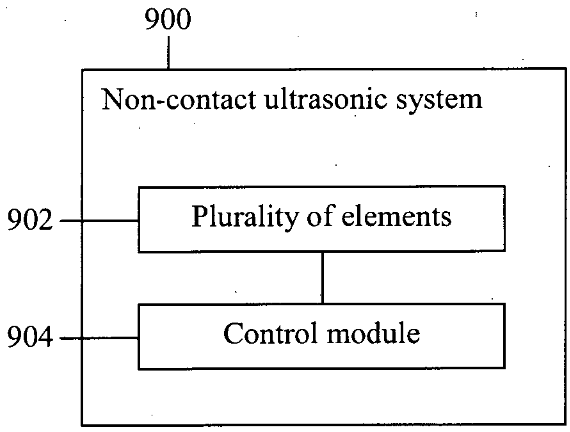
900
Non-contact ultrasonic system
902
Plurality of elements
904
Control module

FIG. 9

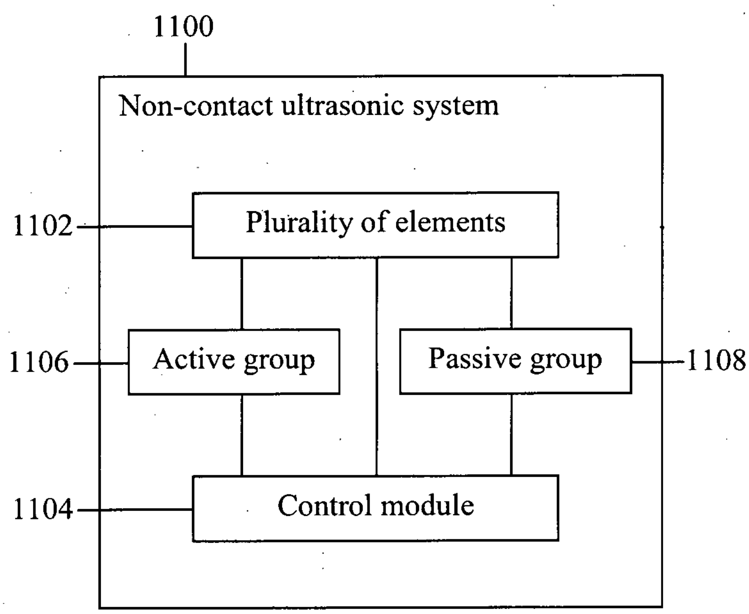
1100
Non-contact ultrasonic system
1102
Plurality of elements
1106
Active group
Passive group
1108
1104
Control module

FIG. 11

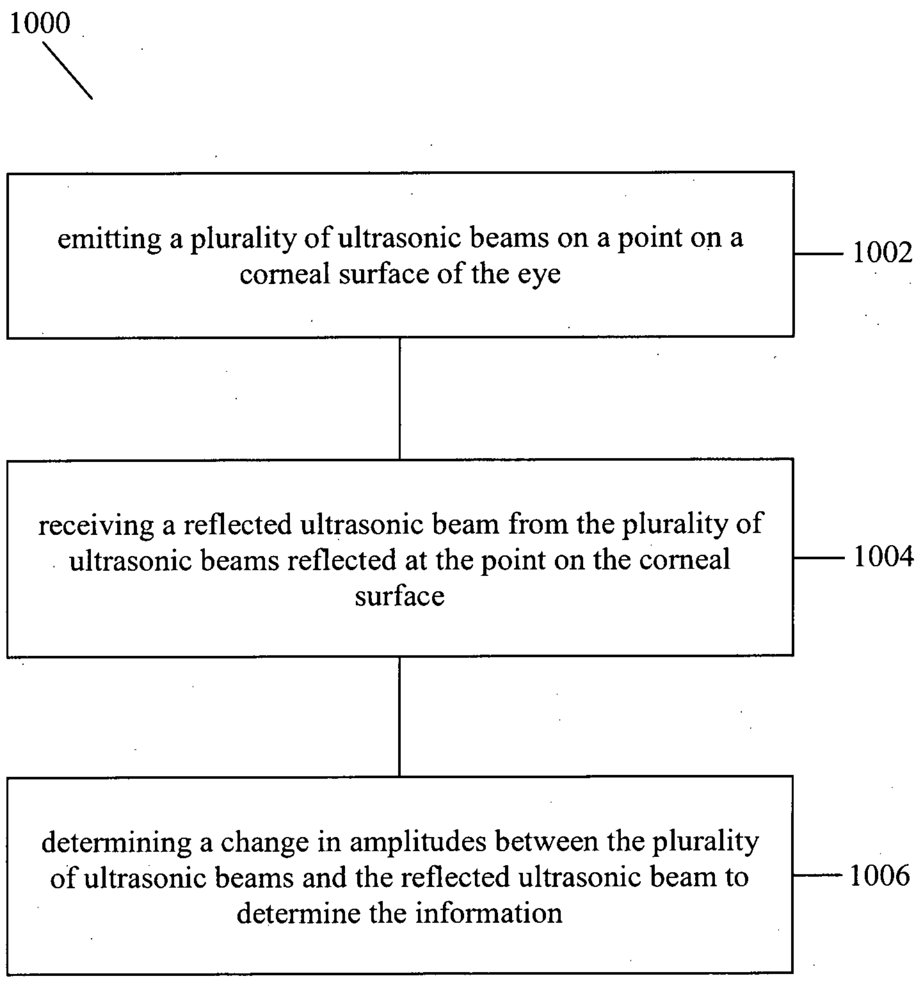
1000
emitting a plurality of ultrasonic beams on a point on a corneal surface of the eye
1002
receiving a reflected ultrasonic beam from the plurality of ultrasonic beams reflected at the point on the corneal surface
1004
determining a change in amplitudes between the plurality of ultrasonic beams and the reflected ultrasonic beam to determine the information
1006

FIG. 10

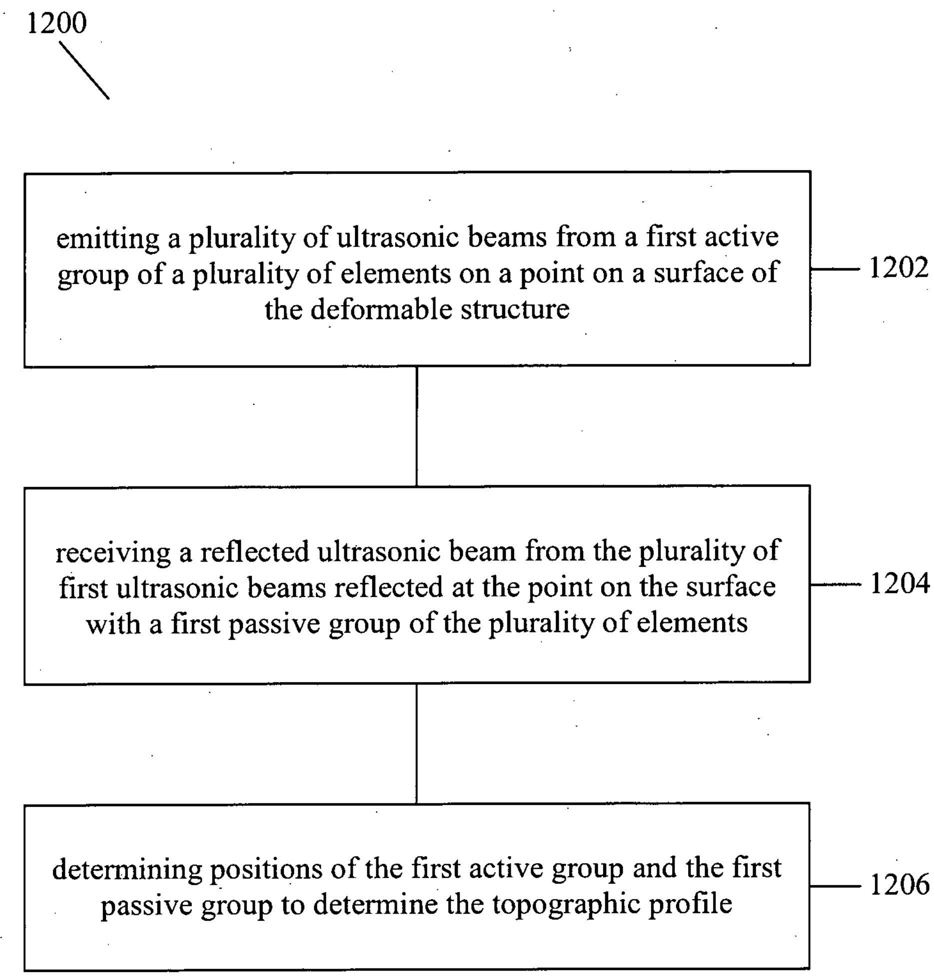
1200
emitting a plurality of ultrasonic beams from a first active group of a plurality of elements on a point on a surface of the deformable structure
1202
receiving a reflected ultrasonic beam from the plurality of first ultrasonic beams reflected at the point on the surface with a first passive group of the plurality of elements
1204
determining positions of the first active group and the first passive group to determine the topographic profile
1206

FIG. 12

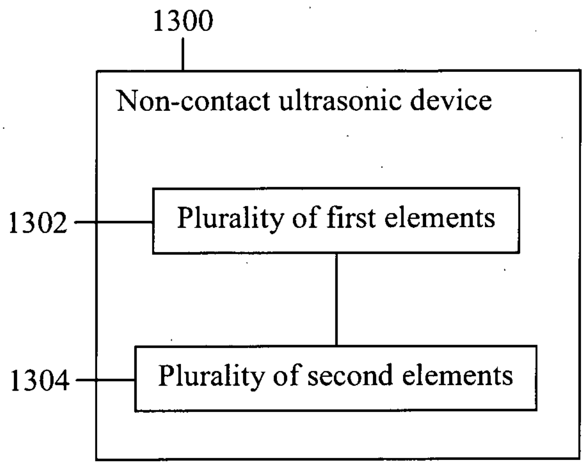
1300
Non-contact ultrasonic device
1302
Plurality of first elements
1304
Plurality of second elements

FIG. 13

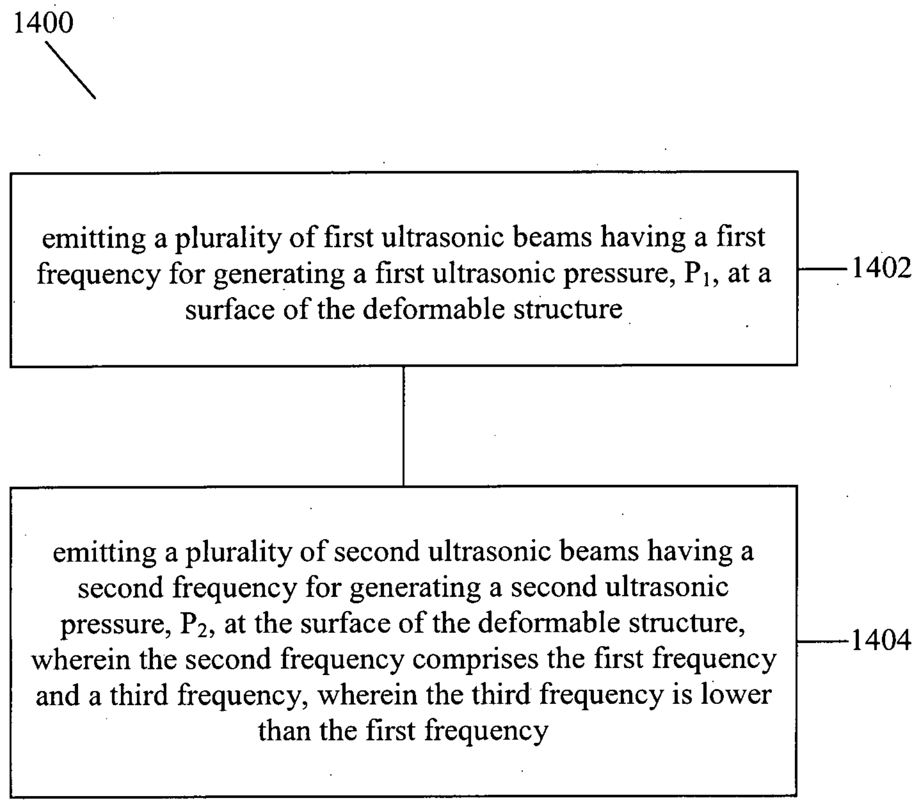
1400
emitting a plurality of first ultrasonic beams having a first frequency for generating a first ultrasonic pressure, $P_1$, at a surface of the deformable structure
1402
emitting a plurality of second ultrasonic beams having a second frequency for generating a second ultrasonic pressure, $P_2$, at the surface of the deformable structure, wherein the second frequency comprises the first frequency and a third frequency, wherein the third frequency is lower than the first frequency
1404

FIG. 14

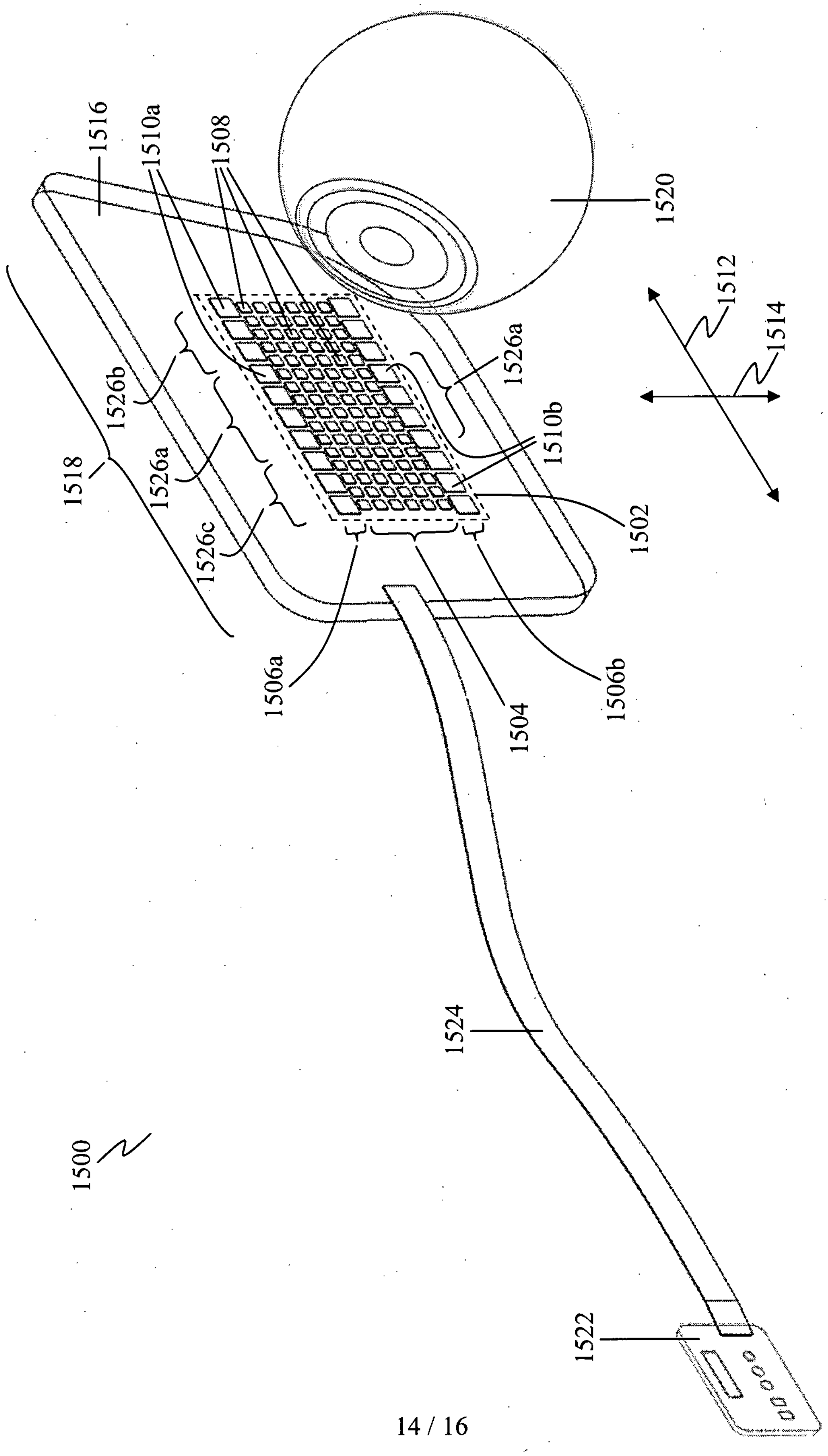
1500
1502
1504
1506a
1506b
1508
1510a
1510b
1512
1514
1516
1518
1520
1522
1524
1526a
1526b
1526c

FIG. 15

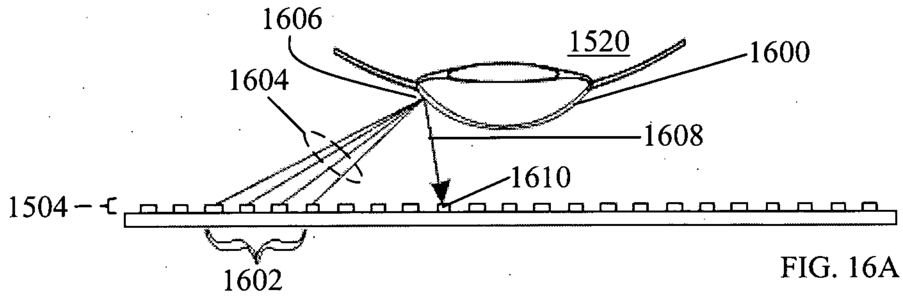


FIG. 16A

Acoustic Beam Steering

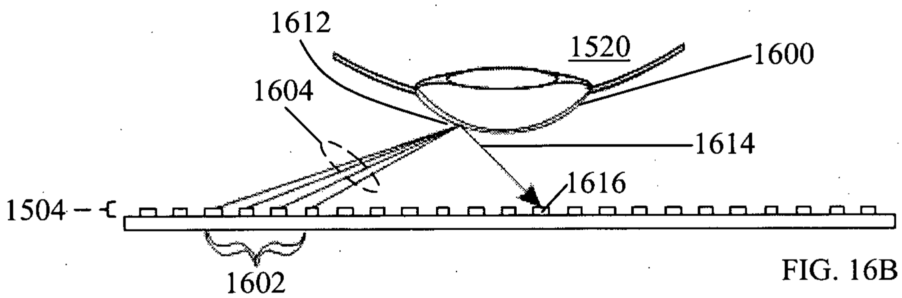


FIG. 16B

Active Elements Shifting

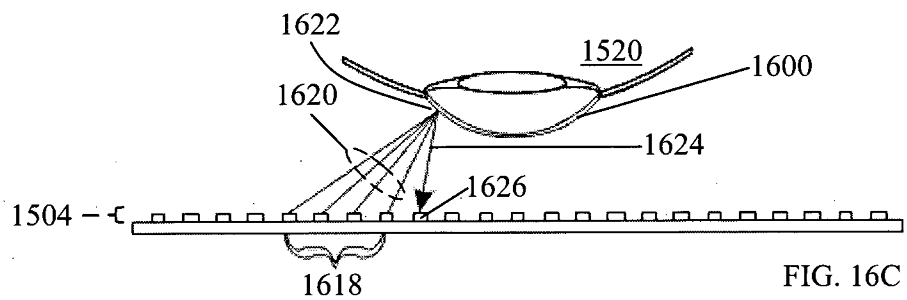


FIG. 16C

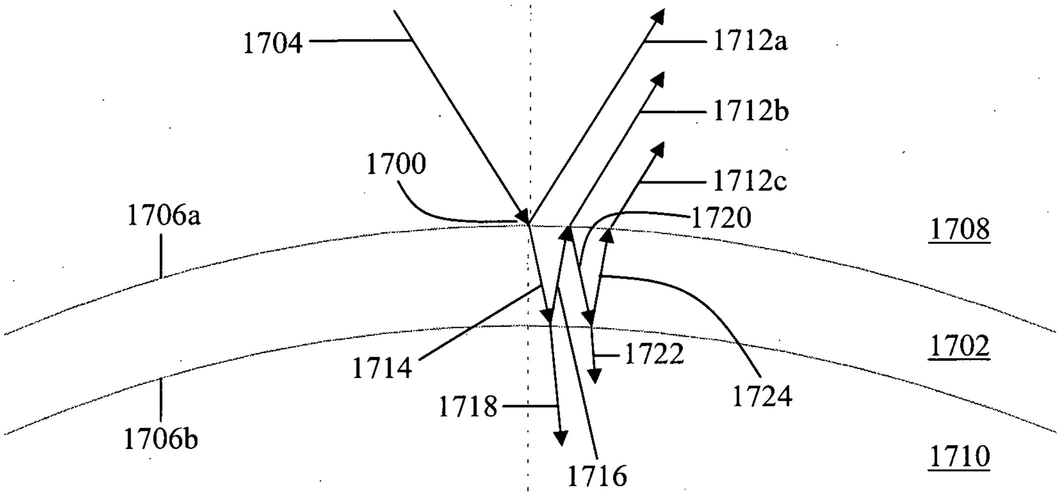
1704
1712a
1712b
1700
1712c
1706a
1720
1708
1714
1722
1702
1718
1724
1706b
1716
1710

FIG. 17

**INTERNATIONAL SEARCH REPORT**

International application No.
**PCT/SG2012/000112**

A. CLASSIFICATION OF SUBJECT MATTER

***A61B 3/16 (2006.01) A61B 8/00 (2006.01) A61B 8/14 (2006.01)***

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, WPI and A61B8-, A61B3-, intraocular, eye, cornea, actuating, receiving, topography, direction, ultrasound, ultrasonic, non contact, transducer, plural, array, grid, matrix, deformable, active, passive, tonometer, intraocular pressure and the like.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| | Documents are listed in the continuation of Box C | |

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 27 July 2012 | 06 August 2012 |

**Name and mailing address of the ISA/AU**

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**Authorized officer**

Viara Van Raad
AUSTRALIAN PATENT OFFICE
(ISO 9001 Quality Certified Service)
Telephone No. +61 2 62223643

| INTERNATIONAL SEARCH REPORT | International application No. |
|---|---|
| C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT | **PCT/SG2012/000112** |

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| | DD 294410 A5 (BEZIRKSKRANKENHAUS POTSDAM) 02 October 1991 | |
| X | Abstract, Fig. 1, pages 1, 3 and 4 | 1-8, 11-19 |
| Y | Abstract, Fig. 1, pages 1-4 | 9, 10, 12, 14, 15, 45-59, 74-81 |
| | US 5636635 A (MASSIE et al.) 10 June 1997 | |
| X | Abstract, Figs. 1A-1F and Figs. 2-9, elements (17), (29), col. 6, ln. 4-col. 7, ln. 42; col. 10, ln. 12- col. 12, ln. 21 | 16-19 |
| Y | col. 9, ln. 15-col. 14, ln. 67 | 9, 10, 12, 14, 15 |
| | US 6030343 A (CHECHERSKY et al. ) 29 February 2000 | |
| X | Abstract, Figs. 1, 4, 5, and Figs. 6A-6C, col. 3, ln. 55-col. 4; ln. 32; col. 6, ln. 3-col. 10, ln. 15 | 16-19, 53-59 |
| Y | Abstract and Figs. 6A-6C | 9, 10, 12, 14, 15, 45-52, 74, 81 |
| | CA 2724222 A1 (UNIVERISTY OF TSUKUBA, JP) 19 November 2009 | |
| Y | para [0020]-[0069], elements (100), (110), (160)-(180), (200), (300), (400) and (600), Figs. 2-4, pattern classification program (402), Fourier Analysis program (401); | 12, 14, 15, 45-59, 74-81 |

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

**See Supplemental Box for Details**

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
**1-19, 45-59, 74-81**

**Remark on Protest**

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

**Supplemental Box**

Continuation of: **Box III**

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- Claims 1-15 are directed to a Non-Contact Ultrasonic Device (NCUD) and a corresponding method of controlling the NCUD, the NCUD comprising a first plurality of ultrasound elements for actuating a corneal surface of an eye and a second plurality of ultrasound elements for sending, receiving and measuring ultrasonic beams from a point of the corneal surface. The feature of the NCUD comprising the two designated pluralities of ultrasound elements is specific to this group of claims.

- Claims 16-19 are directed to a method of controlling a NCUD, the method comprising actuating a corneal surface by emitting ultrasonic beams and further, emitting a plurality of other ultrasound beams and receiving reflected ultrasound beams from this surface. The feature of the said method of controlling the NCUD is specific to this group of claims.

- Claims 20-44 are directed to a system and method of determining an Intra-Ocular Pressure (IOP) of an eye by determining a topographic profile of the corneal surface of the eye, and by determining a tensional force of the corneal surface,the IOP of the eye being determined on the basis of determination of the tensional forces and the already determined topographic profile. The feature of of the said method and system of determining the IOP based on the tensional forces and topographic profile is specific to this group of claims.

- Claims 45-59 are directed to a Non-Contact Ultrasonic System (NCUS) for determining IOP of an eye comprising a topographic profile determination circuit/step and a first and second pluralities of ultrasound elements, the first pluralities of the ultrasound elements designated to actuate the corneal surface, the second plurality of ultrasound elements designated for emitting ultrasound beams that are reflected from the corneal surface and subsequently measured by the second set of ultrasound elements and an IOP determination step/circuit. The feature of of the said NCUS with the topographic and IOP determination circuits/steps is specific to this group of claims.

- Claims 60-67 are directed to a NCUS for determining an information of an eye comprising a plurality of ultrasonic elements configured to emit a plurality of ultrasonic beams toward a point of the eye surface and to receive the reflected ultrasonic beams from the point of the corneal surface, the NCUS comprising a control module that is configured to determine the change in amplitudes between the sent and reflected beams. The feature of of the said NCUS comprising the plurality of ultrasound elements for sending and receiving ultrasound beams and determining the change of the amplitudes between the sent and reflected beams is specific to this group of claims.

- Claims 68-73 are directed to a NCUS for determining a topographic profile of a deformable structure by using a plurality of ultrasonic elements to send ultrasonic beams to a single point of a corneal surface and receive reflected ultrasonic beams from the point of the corneal surface and to determine the positions of

**Supplemental Box**

the plurality of the elements by a control module configured to determine these positions. The feature of of the determination of the positions of these elements of the said NCUS is specific to this group of claims.

- Claims 74-81 are directed to a method of determining a topographic profile of a deformable structure by using two sets of ultrasonic elements, the firs set being a group of active ultrasonic elements and the second set being a set of passive ultrasound elements and determining the positions of the first and second elements to determine the topographic profile of the deformable structure. The feature of of determining the positions of the two sets of ultrasonic elements is specific to this group of claims.

- Claims 82-88 are directed to a method or a system for actuating a deformable structure by a first set of ultrasonic elements sending plurality of ultrasound elements with a first frequency and sending and receiving ultrasound beams with a second frequency by second set of ultrasound elements wherein the second frequency comprises the first frequency and a third frequency. The feature of of actuating the deformable structure by the first set of elements with a first frequency and sending ultrasound beams by the second set of ultrasound elements the second set of the ultrasound beams having second frequency that has the first and a third frequency is specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. The only feature common to all of the claimed inventions and which provides a technical relationship among them is non-contact ultrasonic tonometer to provide ultrasonic beam(s) to the corneal surface of an eye (or to a deformable structure) and to receive the reflected ultrasonic beams form the corneal surface (or the deformable structure).

However this feature does not make a contribution over the prior art because it is disclosed in:
US 6030343 A (CHECHERSKY et al.) published 29 February 2000, This document disclsoes all features of claim 16 (Abstract, Figures), see also US 5636635A (MASSIE et al.) published 10 June 1997 which also dicloses all features of claim 16 (Asbtarct, Figures). DD 294410 A5 (BEZIRKSKRANKENHAUS POTSDAM) published on 02 October 1991 (pages 1-4).

Therefore in the light of this document this common feature cannot be a special technical feature. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied *a posteriori*.

Because no additional search fees were paid, the International Search Report and the Written Opinion of the International Searching Authority was restricted to the invention claimed in claims 1-19, 45-59 and 74-81.

**Supplemental Box**

| INTERNATIONAL SEARCH REPORT<br>Information on patent family members | International application No.<br>**PCT/SG2012/000112** |
|---|---|

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

| **Patent Document/s Cited in Search Report** | | **Patent Family Member/s** | |
|---|---|---|---|
| **Publication Number** | **Publication Date** | **Publication Number** | **Publication Date** |
| DD 294410 A5 | 02 Oct 1991 | None | |
| US 5636635 A | 10 Jun 1997 | EP 0536574 A1 | 14 Apr 1993 |
| | | EP 0536574 B1 | 27 Nov 1996 |
| | | JP 5253190 A | 05 Oct 1993 |
| | | US 5396888 A | 14 Mar 1995 |
| | | US 5636635 A | 10 Jun 1997 |
| | | US 5865742 A | 02 Feb 1999 |
| | | WO 9849941 A1 | 12 Nov 1998 |
| US 6030343 A | 29 Feb 2000 | US 6030343 A | 29 Feb 2000 |
| CA 2724222 A1 | 19 Nov 2009 | CA 2724222 A1 | 19 Nov 2009 |
| | | EP 2294968 A1 | 16 Mar 2011 |
| | | JP 2009273715 A | 26 Nov 2009 |
| | | US 2011118585 A1 | 19 May 2011 |
| | | WO 2009139435 A1 | 19 Nov 2009 |

**End of Annex**

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.