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[Continued on next page]

(54) Title: DARK-FIELD IMAGING

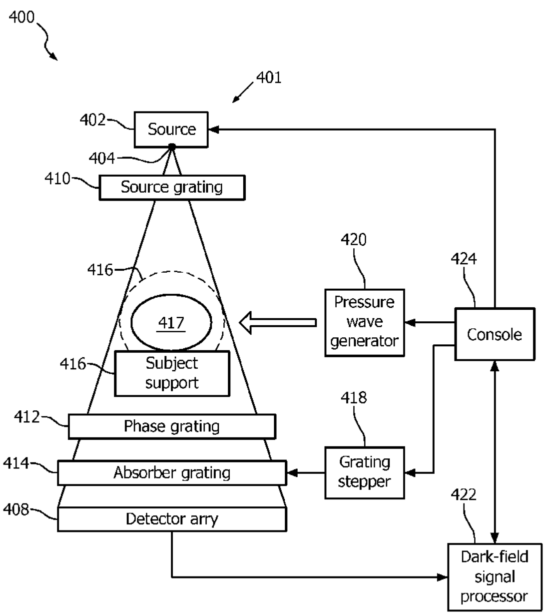

FIG. 4

(57) Abstract: A method for dark-field imaging includes acquiring dark-field image projections of an object with an imaging apparatus that includes an x- ray interferometer, applying a pressure wave having a predetermined frequency to the object for each acquired projection, wherein the predetermined frequency is different for each projection, and processing the acquired projections, thereby generating a 3D image of the object. In other wods, the method corresponds to acoustically modulated X-ray dark field tomography. An imaging system (400) includes a scanner (401) configured for dark-field imaging, the scanner including: a source/detector pair (402/408) and a subject support (416), a pressure wave generator (420) configured to generate and transmit pressure waves having predetermined frequencies, and a console (424) that controls the scanner and the pressure wave generator to acquire at least two dark-field projection of an object with different pressure waves having different frequencies applied to the object.

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DARK-FIELD IMAGING

The following generally relates to dark-field dark field imaging and is described with particular application to computed tomography (CT).

In conventional CT imaging, contrast is obtained through the differences in the absorption cross-section of the constituents of the scanned object. This yields good results where highly absorbing structures such as bones are embedded in a matrix of relatively weakly absorbing material, for example the surrounding tissue of the human body. However, in cases where different forms of tissue with similar absorption cross-sections are under investigation (e.g., mammography or angiography), the X-ray absorption contrast is relatively poor. Consequently, differentiating pathologic from non-pathologic tissue in an absorption radiograph obtained with a current hospital-based X-ray system remains difficult for certain tissue compositions.

Dark-field (or grating-based differential phase-contrast) imaging overcomes the above-noted contrast limitation. Generally, such imaging utilizes X-ray gratings, which allow the acquisition of X-ray images in phase contrast, which provides additional information about the scanned object. With dark-field imaging, an image is generated that is based on the scatter components of the X-ray radiation diffracted by the scanned object. Very slight density differences in the scanned object then can be shown at very high resolution. An example imaging system configured for dark-filed imaging is discussed in application serial number 13/514,682, filed June 8, 2012, entitled “Phase Contrast Imaging,” and assigned to Koninklijke Philips Electronics N.V., the entirety of which is incorporated herein by reference.

The apparatus described in 13/514,682 is shown in FIGURE 1 and includes an X-ray source 102 and a detector array 104 located opposite each other across an examination region 106. A source grating 108 is adjacent to the source 102, an absorber (or analyzer) grating 110 is adjacent to the detector array 104, and a phase grating 112 is between an object 114 and the absorber grating 110. The source grating 108 is separated from the phase grating 112 by a distance (“l”) 116. The phase grating 112 is separated from the absorber grating 110 by a distance (“d”) 118, which corresponds to the Talbot distance ($d = p_1^2/8\lambda$, where λ is the wavelength of the incident radiation).

The source grating 108, the phase grating 112, and the absorber grating 110 respectively have grating line periods p_0, p_1 and p_2, where $p_2 = \frac{1}{d} p_0$ and $p_2 = \frac{1}{2} p_1 \cdot \frac{(d+l)}{l}$. The source grating 108 creates an array of individually coherent, but mutually incoherent sources. The object 114 in the beam path causes a slight refraction for each coherent subset of X-rays, which is proportional to the local phase gradient of the object. This small angular deviation results in changes of the locally transmitted intensity through the combination of the phase gratings 112 and the absorber grating 110.

The phase grating 112 acts as a beam splitter and divides an incoming X-ray beam essentially into the two first diffraction orders. The diffracted beams interfere and form, in Talbot distances, linear periodic fringe patterns with a periodicity that equals half the phase grating times the geometric magnification factor defined by l / (l+d). Perturbations of the incident wave front, such as those induced by refraction on the object 114 in the beam, lead to local displacement of the fringes. The absorber grating 110 acts as a transmission mask for the detector array 104 and transforms local fringe positions into signal intensity variations. The detected signal profile hence contains quantitative information about the phase shift induced by the object 114.

To code and extract the phase information, a phase-stepping approach has been utilized. With this approach, the absorber grating 110, relative to the phase grating 112, is translated in a transverse direction, which is perpendicular to the lines of gratings, via predetermined step size movements over a grating lines period. At each grating step, a measurement is taken, and several (e.g., eight) grating steps and measurements are taken for a projection. For 3D acquisitions, the object 114 is rotated relative to the source 102, the gratings 108, 110 and 112, and the detector array 104, or the source 102, the gratings 108, 110 and 112, and the detector array 104 are rotated around the object 114 (over at least 180 degrees plus a fan angle), with a predetermined number of projections (e.g., 1000) acquired from different angular views of the rotation.

Each pixel in the dark field image represents a line integral of the second moment of the small angle scattering distribution. However, the contribution to the line integral depends on the relative position of the object 114 in the examination region 106 between the source 102 and detector array 104, due to inverse signal magnification. This is shown in FIGURES 2 and 3. In FIGURE 2, the object 114 is closer to the source 102 relative to the position of the object 114 in FIGURE 3. As a result, a maximum height 202 of a detector array profile 200 for the object location in FIGURE 2 will be smaller relative to a maximum height 302 of a detector array profile 300 for the object location in FIGURE 3.

Generally, inverse signal magnification scales the height of the detected signal inversely with respect to the position of the object 114 between the source 102 and the detector array 104.

The attenuation of an X-ray along a path from the source 102 through the object 114 and to the detector array 104 occurs as shown in EQUATION 1:

EQUATION 1:

$$I = I_0 e^{-\int_0^1 l f(\vec{S}+l\vec{r})dl}$$

where I is the detected signal (dark field projection value) at the detector pixel, I_o is the unattentuated detected signal, l is the position along the x-ray from the source 102 (l=0) through the object 114 to a detector pixel of the detector array 104 (l=1), $f(\cdot)$ is the the distribution of the object property, $\vec{S}$ is the source position, and $\vec{r}$ is a unit vector along the x-ray from the source 102 to the phase grating 112. Logging both sides of the equations renders a linear equation representing the line integral of the attenuation coefficient along a path, as shown in EQUATION 2:

EQUATION 2:

$$h = -\ln\left(\frac{I}{I_0}\right) = \int_0^1 l f(\vec{S} + l\vec{r})dl,$$

where h is the measurable signal. The goal is to reconstruct the distribution of the property $f(\cdot)$ along the ray $\vec{r}$.

Unfortunately, to rotate the source 102, the gratings 108, 110 and 112, and the detector array 104, the imaging system must at least include a rotating frame that supports the source 102, the detector and the gratings 108, 110 and 112, a stationary frame and bearing to support the rotating frame, a belt, chain, magnetic or other drive system along with a motor and controller to rotate the rotating frame, and one or more encoders or the like to determine angular position information, which adds complexity and cost to the overall dark field imaging system. In addition, the rotating components are under g forces, which cause dynamic structural changes to the rotating components during each rotation, which may increase the mechanical requirements and tolerances of the phase stepping components so the grating is accurately stepped for each measurement.

Aspects described herein address the above-referenced problems and others.

In one aspect, a method for dark-field imaging includes acquiring dark-field image projections of an object with an imaging apparatus that includes an x-ray interferometer, applying a pressure wave having a predetermined frequency to the object for each acquired projection, wherein the predetermined frequency is different for each projection, and processing the acquired projections, thereby generating a 3D image of the object.

In another aspect, an imaging system includes a scanner configured for dark-field imaging, the scanner including: a source/detector pair and a subject support, a pressure wave generator configured to generate and transmit pressure waves having predetermined frequencies, and a console that controls the scanner and the pressure wave generator to acquire at least two dark-field projection of an object with different pressure waves having different frequencies applied to the object.

In another aspect, a method includes generating a 3D dark-field image of an object with data acquired without a relative movement between a source/detector pair of an imaging system scanning the object and the object and by applying pressure waves having different frequencies for each acquired projection.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 schematically illustrates a prior art apparatus configured for dark-field imaging.

FIGURES 2 and 3 schematically illustrate how object position magnification along a ray affects dark-field imaging.

FIGURE 4 schematically illustrates an imaging system configured for 3D dark-field grating-based DPCI imaging.

FIGURE 5 illustrates an example method for 3D dark-field grating-based DPCI imaging.

Referring to FIGURE 4, an imaging system 400 includes a scanner 401 configured for at least 3D dark-field imaging is schematically illustrated. The scanner 401 includes a radiation source 402 (e.g., an X-ray tube) with a focal spot 404 that emits radiation that traverse an examination region 406 and an object 417 or subject therein. A radiation sensitive detector array 408 is located opposite the radiation source 402 across the examination region 406. The radiation sensitive detector array 408 detects radiation traversing the examination region 406 and generates a signal indicative thereof, including a dark-field signal in connection with dark-field imaging.

An X-ray imaging interferometer includes three grating structures, a source grating 410, a phase grating 412 and an absorber grating 414. The source grating 410, phase grating 412 and absorber grating 414 respectively have grating line periods and are separated by distances, e.g., as discussed in application serial number 13/514,682, filed June 8, 2012, entitled "Phase Contrast Imaging," and assigned to Koninklijke Philips Electronics N.V., the entirety of which is incorporated herein by reference. Generally, the source grating 410 is adjacent to the focal spot 404 in the path of the radiation, acts as an absorbing mask with transmitting slits, filters the emitted radiation beam, and creates individual coherent (but mutually incoherent) sources.

The object causes refraction of coherent x-rays that is proportional to the local gradient of the real part of the refractive index of the object, and the angular deviation results in changes of the locally transmitted intensity through the phase grating 412. The phase grating 412 is located adjacent to the object and acts as a beam splitter, dividing an incoming x-ray into diffracted beams that interfere and form linear periodic fringe patterns. The absorber grating 414 acts as a transmission mask for the detector 408 and transforms local fringe positions into signal intensity variations. The phase/absorber gratings 412/414 can be considered a multi-collimator translating the angular deviations into changes of the locally transmitted intensity, which can be detected with a standard or other imaging detector array.

The phase grating 412 and the absorber grating 414 are configured to translate, relative to one another, in a transverse direction, perpendicular to the z-axis. This includes translating one or both (in a same direction with different speeds or an opposing direction with the same or different speed) of the phase grating 412 and the absorber grating 414 in the transverse direction. For explanatory purposes, the following with be discussed with respect to a configuration in which the absorber grating 414 translates. A grating stepper 418 controls translation (i.e., stepping) of the absorber grating 414 at least based on a phase stepping algorithm which moves the absorber grating 414 in predetermined discrete step size increments.

A pressure wave generator 420 generates and transmits a pressure wave that traverses the examination region 406 and the object 417 therein. The pressure wave generator 420 may include a transducer or the like that can convert one form of energy (e.g., electrical) into a pressure wave of a predetermined frequency. Suitable frequencies are frequencies between one Hertz (1 Hz) and one thousand Hertz (1000 Hz), which cause compression and/or vibration of the material of the object 417 that results in physical deformation of the object 417 in the examination region 406 which is similar to actual physical displacement of the object 417 in the examination region 406.

A general-purpose computing system or computer serves as an operator console 424. The console 424 includes a human readable output device such as a monitor and an input device such as a keyboard, mouse, etc. Software resident on the console 424 allows the operator to interact with and/or operate the imaging system 400. Such interaction includes selecting a dark-field imaging scan protocol which utilizes the pressure wave generator 420, initiate scanning, etc. A subject support 416 supports the object 417 in the examination region 406.

With one dark-field imaging protocol, the pressure wave generator 420 is invoked to transmit a pressure wave that traverses the object 417 and the grating stepper 418 steps the absorber grating 414 through phase coding steps for acquisition of a projection, a pressure wave having a different frequency is generated for different projections, and the projections are acquired with no relative movement between the source/detector pair 402/408 and the object 417. The number of phase coding steps and/or projections can be default, user defined, and/or otherwise determined.

With such an algorithm, the pressure waves interacts with the material of the object 417 and such interactions result in different material deformations of the object 417 for each projection, which, effectively, is similar to physically moving the object 417 along a ray path between the source 402 and the detector array 408. Since the dark field signal h is a function of distance of the object 417 from the source 402, the resulting set of projections include information that can be used to determine attenuation along each ray, which is described is greater detail next.

As discussed above, the dark field signal h has been represented as shown in EQUATION 2, which is reproduced below:

EQUATION 2:

$$h = -\ln\left(\frac{I}{I_0}\right) = \int_0^1 l f(\vec{S} + l\vec{r})\, dl.$$

Because of the low compressibility of tissue, tissue reacts with a local displacement in a pressure wave. Under ideal conditions, the displacement Δ_l can be model along $\vec{r}$ under a pressure wave excitation as shown in EQUATION 3:

EQUATION 3:

$$\Delta_l = ae^{-i(tk_t+(\vec{S}+l\vec{r})k_{\vec{r}})},$$

where a is the amplitude of the displacement, i is sqrt(-1), k_t is the frequency of the sound wave, k_r is the wavelength, and t is time. For a snapshot $(t = constant)$, a constant part C (for each ray) can be separated from the displacement along $\vec{r}$ using a parameter l as shown in EQUATION 4:

EQUATION 4:

$$\Delta_{M,l} = C_M e^{-ilk_{M,l}},$$

where M is a set of wave excitation parameters and $M = \{a_M, C_M, k_{M,l}\}$.

The dark field imaging measurement h, as a function of local displacement, and based on EQUATIONS 2 and 4, can be expressed as shown in in EQUATION 5:

EQUATION 5:

$$h(M) = \int(l + \Delta_{M,l}) f(\vec{S} + l\vec{r}) dl.$$

With a reference measurement $h(M_0), \Delta_{M_0,l} = 0$, EQUATION 5 can be written as shown in EQUATION 6:

EQUATION 6:

$$h(M) = h(M_0) + \int \Delta_{M,l} f(\vec{S} + l\vec{r}) dl = h(M_0) + C_M \int e^{-ilk_{M,l}} f(\vec{S} + l\vec{r}) dl.$$

With a set of modulations, EQUATION 6 becomes a Fourier transformation.

A dark-field signal processor 422 processes the dark-field signals generated and output by the detector array 408, producing 3D data of the scanned object 417. This includes inverting the Fourier transformation and reconstructing the distribution of the property $f(\cdot)$ along the ray $\vec{r}$, creating a 3D image of the object. Where inhomogeneous elastic properties of the tissue disturb the displacement field, an iterative reconstruction and a discrete formulation of the measurement can be used to solve for an elasticity field and the dark field in one combined reconstruction.

FIGURE 5 illustrates an example dark field imaging method with no physical movement of the source/detector pair 402/480 and the object 417 between projections.

It is to be appreciated that the ordering of the acts is not limiting. As such, other orderings are contemplated herein. In addition, one or more acts may be omitted and/or one or more additional acts may be included.

At 502, a reference projection of a dark-field scan of the object 417 is acquired with no relative movement between the source/detector pair 402/480 and the object 417.

At 504, a pressure wave having a predetermined frequency is applied to the object, which causes a deformation of the object 417 similar to actual physical displacement of the object 417 along a ray path between the source 402 and the detector 408.

At 506, a next projection of the dark-field scan of the object 417 under the first deformation is acquired with no relative movement between the source/detector pair 402/480 and the object 417.

At 508 it is determined whether another projection is to be acquired.

If so, then acts 504 and 506 are repeated with a pressure wave having a next different frequency.

If not, then at 510 the projections are processed to generate a 3D image of the object 417.

The above methods may be implemented by way of computer readable instructions, encoded or embedded on computer readable storage medium, which, when executed by a computer processor(s), cause the processor(s) to carry out the described acts. Additionally or alternatively, at least one of the computer readable instructions is carried by a signal, carrier wave or other transitory medium.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be constructed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS:

1. A method for dark-field imaging, comprising:
acquiring dark-field image projections of an object with an imaging apparatus that includes an x-ray interferometer;
applying a pressure wave having a predetermined frequency to the object for each acquired projection, wherein the predetermined frequency is different for each projection; and
processing the acquired projections, thereby generating a 3D image of the object.

2. The method of claim 1, wherein the pressure wave causes a deformation of material of the object.

3. The method of any of claims 1 to 2, wherein the projection is acquired with no relative movement between a source/detector pair (402/408) of the imaging apparatus and a subject support (416) of the imaging apparatus supporting the object for the scan.

4. The method of any of claims 1 to 3, wherein a pressure is applied to the object during acquisition of a projection.

5. The method of any of claims 1 to 4, further comprising:
acquiring a reference dark-field image projection without any pressure wave applied to the object.

6. The method of any of claims 1 to 5, wherein the predetermined frequency is a frequency in a range of 1 Hz. to 1000 Hz.

7. The method of any of claims 1 to 6, wherein the acquired projections represent a Fourier transformation.

8. The method of claim 7, further comprising:
generating the 3D image of the object by inverting the Fourier transform and reconstructing a distribution along each ray traversing the object.

9. The method of any of claims 1 to 6, further comprising:
iteratively reconstructing and a discrete formulation of the acquired projections, thereby solving an elasticity field and the dark field in a single combined reconstruction.

10. The method of any of claims 1 to 9, further comprising:
stepping an absorber grating of an interferometer of the imaging apparatus to phase code the projection.

11. An imaging system (400), comprising:
a scanner (401) configured for dark-field imaging, the scanner including: a source/detector pair (402/408) and a subject support (416);
a pressure wave generator (420) configured to generate and transmit pressure waves having predetermined frequencies; and
a console (424) that controls the scanner and the pressure wave generator to acquire at least two dark-field projections of an object with different pressure waves having different frequencies applied to the object.

12. The method of claim 11, wherein the pressure wave causes a deformation of material of the object.

13. The imaging system of any of claims 11 to 12, further comprising:
an interferometer, including:
a source grating (410),
a phase grating (412), and
an absorber grating (414); and
a grating stepper (418) that steps at least one of the phase grating or the absorber grating with respect to the other to phase code the projections.

14. The imaging system of any of claims 11 to 13, wherein the projection is

acquired with no relative movement between the source/detector pair (402/408) and the subject support (416).

15. The imaging system of any of claims 11 to 14, wherein the console controls the scanner and the pressure wave generator to acquire a reference dark-field projection of the object with no pressure applied to the object.

16. The imaging system of any of claims 11 to 15, wherein the predetermined frequency is a frequency in a range of 1 Hz. to 1000 Hz.

17. The imaging system of any of claims 11 to 15, further comprising:
a dark-field signal processor (422) that processes acquired dark-field signals and generates a 3D image of the object.

18. The imaging system of claim 17, wherein the acquired dark-field signals represent a Fourier transformation, and the dark-field signal processor inverts the Fourier transform and reconstructs a distribution along each ray traversing the object, thereby generating the 3D image of the object.

19. The imaging system of any of claims 11 to 15, further comprising:
a dark-field signal processor (422) that iteratively reconstructs and a discrete formulation of the acquired projections, thereby solving an elasticity field and the dark field in a single combined reconstruction.

20. A method, comprising:
generating a 3D dark-field image of an object with data acquired without a relative movement between a source/detector pair of an imaging system scanning the object and the object and by applying pressure waves having different frequencies for each acquired projection.

21. The method of claim 20, wherein the pressure wave causes a deformation of material of the object.

22. The method of any of claims 20 to 21, wherein each pressure wave is applied

to the object during acquisition of a projection.

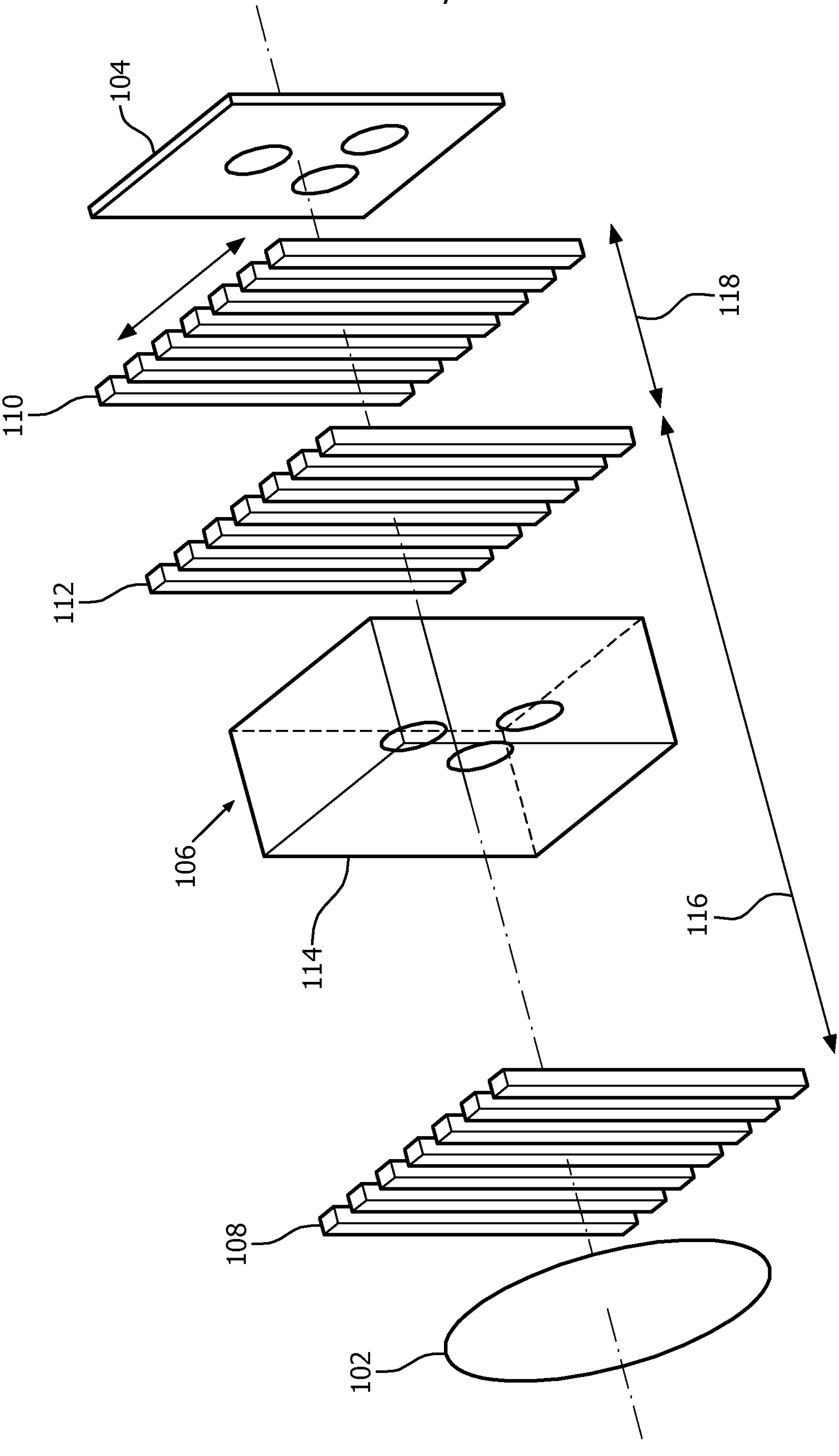

FIG. 1 (Prior art)

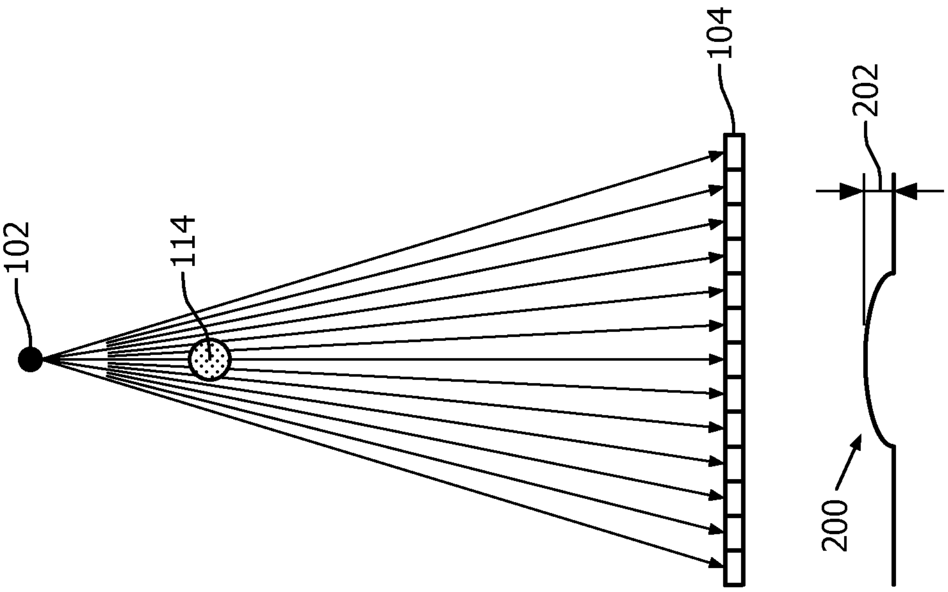

FIG. 2

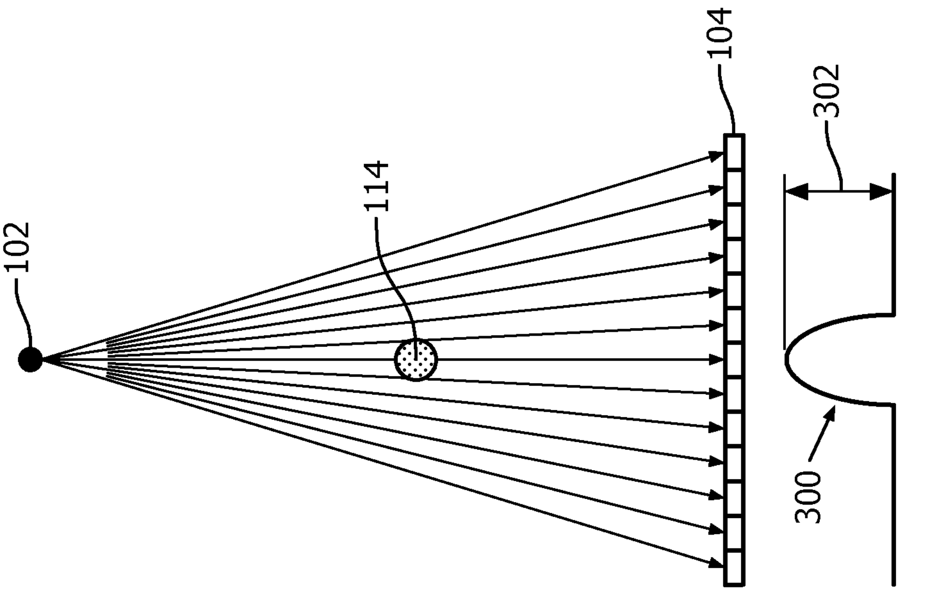

FIG. 3

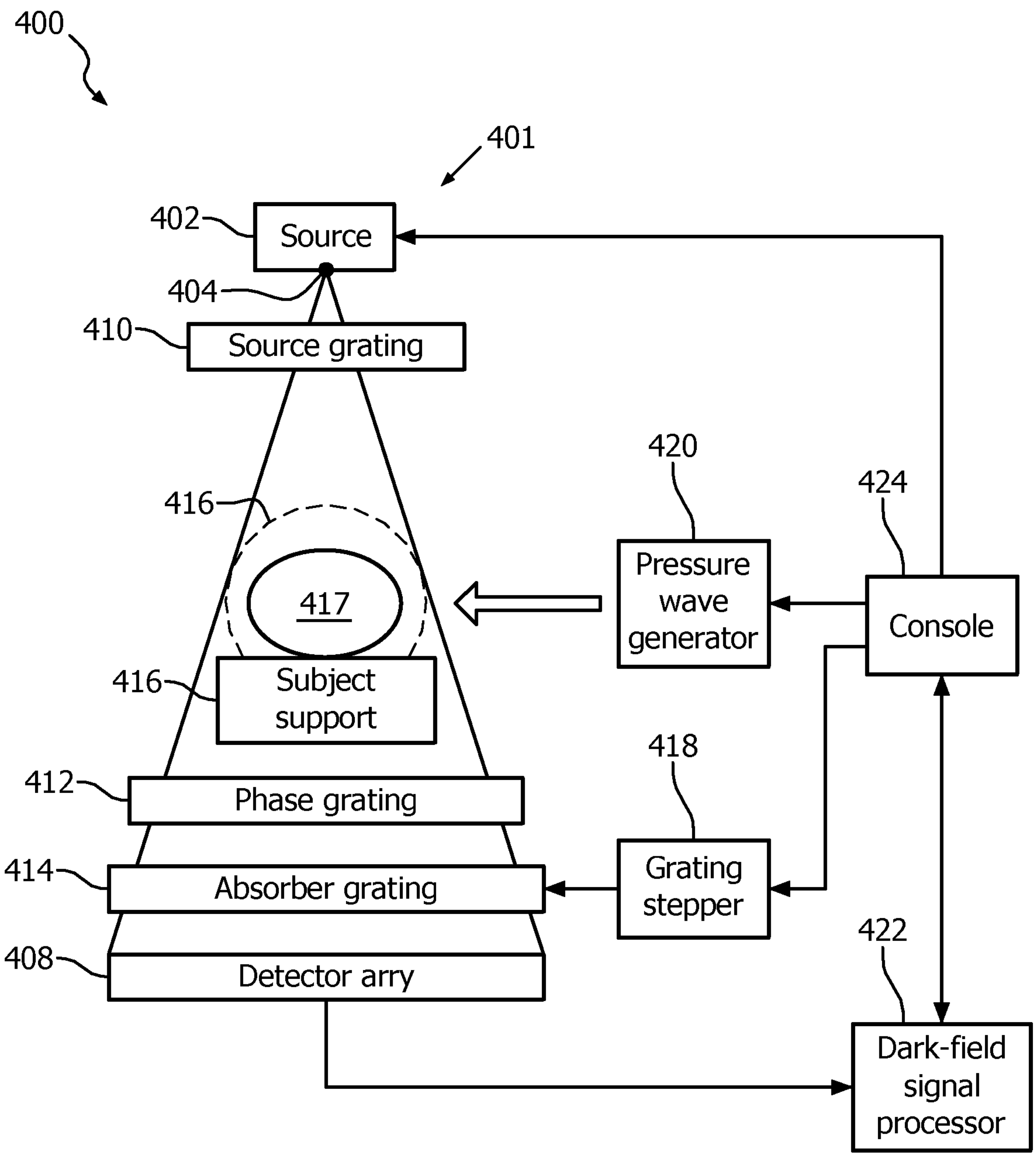
400
401
402
Source
404
410
Source grating
416
417
416
Subject support
412
Phase grating
414
Absorber grating
408
Detector arry
420
Pressure wave generator
424
Console
418
Grating stepper
422
Dark-field signal processor

FIG. 4

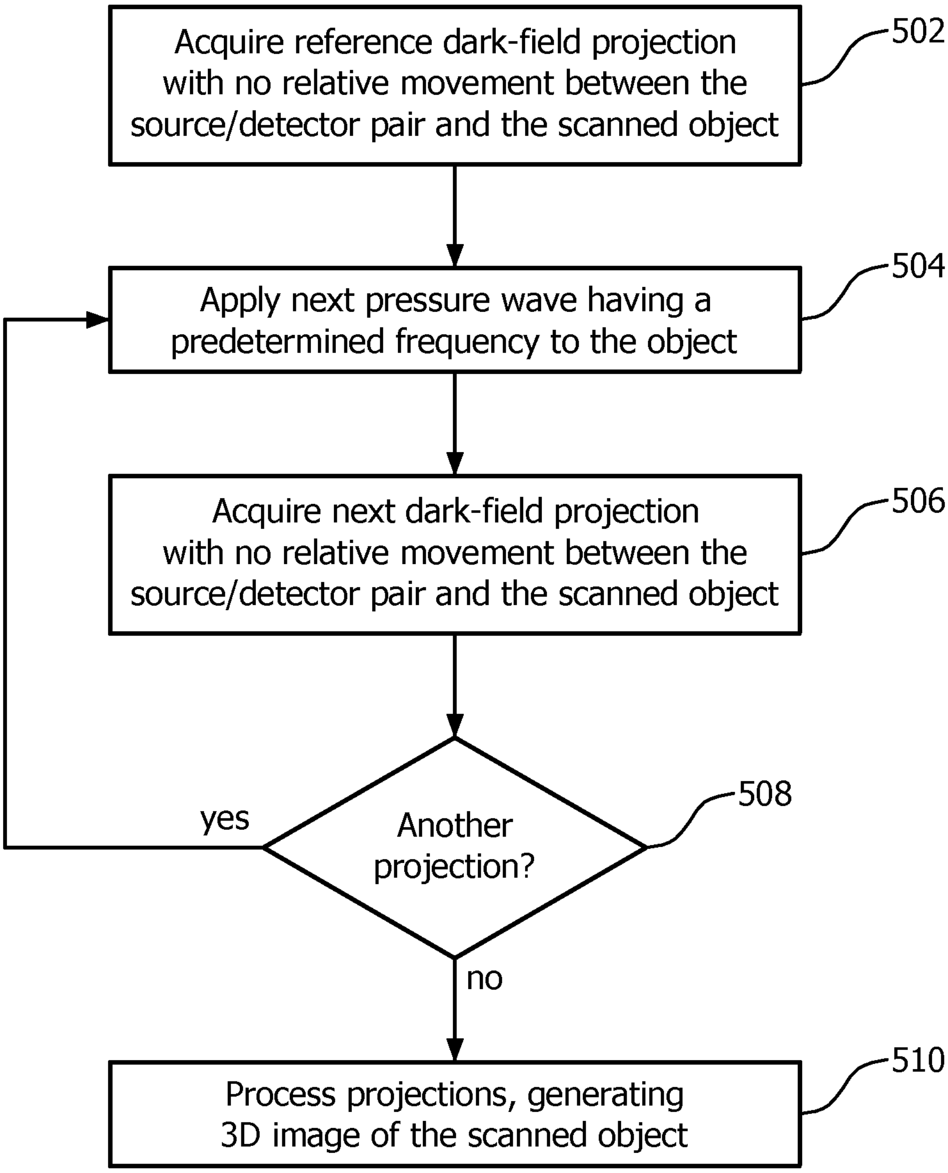
Acquire reference dark-field projection with no relative movement between the source/detector pair and the scanned object
502
Apply next pressure wave having a predetermined frequency to the object
504
Acquire next dark-field projection with no relative movement between the source/detector pair and the scanned object
506
yes
Another projection?
508
no
Process projections, generating 3D image of the scanned object
510

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/055244

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N23/04 G06T11/00 A61B6/03
ADD.

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)
G01N G06T A61B

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2010/074395 A1 (POPESCU STEFAN [DE]) 25 March 2010 (2010-03-25) paragraphs [0002], [0042], [0043] figures 1,2 -----	1-22
A	THERON J. HAMILTON ET AL: "Ultrasonically modulated x-ray phase contrast and vibration potential imaging methods", PROCEEDINGS OF SPIE, vol. 6086, 608601, 9 February 2006 (2006-02-09), pages 1-11, XP055088626, ISSN: 0277-786X, DOI: 10.1117/12.640287 abstract Section 1.2 figures 6-8 -----	1-22

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

* Special categories of cited documents :

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

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Date of the actual completion of the international search	Date of mailing of the international search report
20 November 2013	26/11/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Couteau, Olivier

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International application No
PCT/IB2013/055244

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WANG L V ET AL: "FREQUENCY-SWEPT ULTRASOUND-MODULATED OPTICAL TOMOGRAPHY OF SCATTERING MEDIA", OPTICS LETTERS, THE OPTICAL SOCIETY, vol. 23, no. 12, 15 June 1998 (1998-06-15), pages 975-977, XP000766613, ISSN: 0146-9592 abstract page 975, left-hand column, paragraph 3 - page 977, left-hand column, paragraph 1 figures 1-3 -----	1-22

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2013/055244

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