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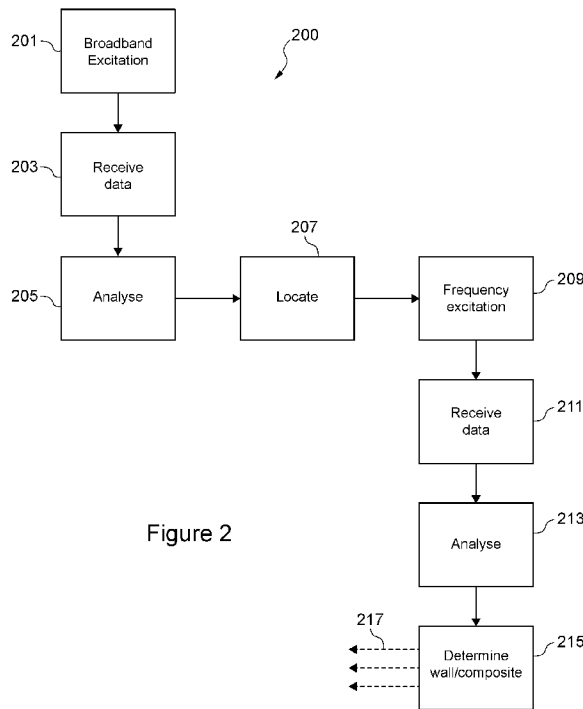


Figure 2

(57) Abstract: The invention provides a method and apparatus for acoustically inspecting a composite repair on a metal structure, the composite repair comprising at least one layer of a composite material applied to a metal substrate of the structure in a repair zone. The method comprises exciting the composite repair within the repair zone using a broadband acoustic excitation signal, and receiving and analysing acoustic data from the first acoustic scan to determine at least one approximate location of one or more defects in the repair zone. In a second acoustic scan, the composite repair is excited in the at least one approximate location using an acoustic excitation signal with frequency characteristics selected to excite the composite material in preference to the metal substrate, and receiving and analysing acoustic data from the second acoustic scan to enable the one or more defects to be characterised as being present in the least one layer of a composite material or present in the metal substrate. In an aspect of the invention, an acoustic probe assembly comprises



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a housing and first and second acoustic transducer subassemblies arranged in the housing. The first and second acoustic transducer subassemblies are configured to enable operation as a transmitter and a receiver respectively, and each of the transducer subassemblies is elongated along a respective axis of orientation, has a first end configured to contact against a material to be inspected, and is axially movable within a respective bore of the housing. The first ends of the first and second transducer subassemblies are biased towards an extended position in a direction towards the first ends; and the axes of the first and second transducers are inclined towards one another.

1 ACOUSTIC INSPECTION METHOD AND APPARATUS THEREFOR

2

3 The present invention relates to the field of acoustic inspection, and in particular to a
4 method and apparatus for acoustic inspection of composite repairs of metal structures,
5 pressure vessels, pipework and pipelines.

6

7 Background to the invention

8

9 Over recent years, composite repairs, made of materials such as glass fibre reinforced
10 polymer (GFRP) and carbon fibre reinforced polymer (CFRP), have been increasingly
11 used as a means of repairing impaired pressure containment vessels, pipes, and other
12 load bearing structures within the oil and gas sector. Although these repairs have brought
13 benefits in terms of improved integrity and reduced downtime, there have also been some
14 instances of failure in these repairs. Such failures have been attributed to factors including
15 poor installation practices, inadequate design and use in unsuitable applications.

16

17 Due to the load-bearing requirements of vessels, pipework, and other structures, a good
18 bond between the installed composite repair and the metal is critical in ensuring sufficient
19 transfer of loads and a successful repair. Accordingly, bonding defects at the composite-
20 metal interface, such as kissing bonds, can be detrimental to the longevity of these repairs.
21 In addition, defects in either the composite repair or the metal structure, such as volumetric
22 flaws, can also be contributing factors to repair failure. As such, within the oil and gas
23 sector there is a need for in-service inspection systems which can inspect and monitor the
24 structural integrity of composite repairs applied to metal structures, providing early cues to
25 potential failures.

26

27 Several commercial ultrasonic inspection techniques already exist which go some way
28 towards solving this problem. However, all of them are considered to have limitations of
29 some kind, impacting their industrial applicability. Such limitations may include their
30 sensitivity to defects and flaws of small dimensions, their ability to be applied to a wide
31 range of geometries, and their ability to be applied to the inspection of composite repairs.

32

33 US2018106765 describes a handheld ultrasonic inspection probe used for determining the
34 bond quality between a thermal protection system material and a composite. Although this
35 technique is said to be able to reveal possible unbonds or kissing bonds, the nature of the

1 probe design means it is only applicable where the substrate surface being scanned is
2 relatively flat.

3

4 US2022003714 relates to a handheld device which can scan surfaces of composite
5 materials exhibiting varying surface profiles, to detect sub-surface material defects. The
6 device includes a number of differently shaped attachments which fit onto the ultrasound
7 probe enabling conformal contact between the probe and a variety of surface
8 morphologies. Although this method goes part way towards addressing the issue of
9 scanning irregularly shaped surfaces it is only applicable to very specific surface
10 geometries.

11

12 US2018003680 describes a method for inspecting coated plates and pipes, using an
13 electromagnetic acoustic transducer (EMAT) based inline inspection (ILI) tool. Using this
14 inspection tool, optimum operating frequencies are determined at roughly 325kHz and
15 425kHz. During inspection, the structure is initially excited using broadband ultrasonic
16 guided waves. One or more narrow frequency bands are then selected based on this
17 acquired data, and the structure is then inspected using ultrasonic guided waves in these
18 narrow frequency bands. By identifying these narrow frequency bands, US2018003680
19 describes that particular layers in the structure can essentially be ignored during
20 inspection.

21

22 US4509369 uses the concept of focussing an ultrasonic beam to increase the sensitivity in
23 detecting near-surface flaws. The probes are angled to better detect near-surface flaws
24 and their depth in pressure vessels, specifically between carbon steel and an inner
25 cladding of stainless steel.

26

27 These known methods attempt to solve different issues associated with the identification of
28 defects within composite materials. However, none of them fully address the issues
29 present in the inspection of composite repairs within oil and gas pipelines, pressure
30 containing vessels, and other structures. In particular, they lack the ability to detect the
31 nature and depth of the defects at a sufficient level of detail, in situations where the pipes
32 have irregular and complex geometries.

33

34 Sonomatic has developed an inspection technology marketed as Dynamic Response
35 Spectroscopy (DRS), which can be used for the inspection of repairs on pipes. This

1 technology relies on a tracker system which keeps the transducer at a precise angle and
2 distance from the repair. As a consequence, the technology can only be used on repairs
3 applied to straight pipe segments.

4

5 US6234025 uses the concept of focussing an ultrasonic beam to increase the sensitivity in
6 detecting near-surface flaws. A lens is used to focus an ultrasound beam in an area of
7 interest, enabling imaging of disbonds and delaminations between repair patches and
8 aircraft parts.

9

10 The Sonomatic system and the apparatus of US6234025 both lack the ability to detect the
11 nature and depth of the defects at a sufficient level of detail, in situations where irregular
12 and complex geometries are present.

13

14 Summary of the invention

15

16 According to a first aspect of the invention, there is provided a method of acoustically
17 inspecting a composite repair on a metal structure, the composite repair comprising at
18 least one layer of a composite material applied to a metal substrate of the structure in a
19 repair zone, wherein the method comprises:

20 - in a first acoustic scan, exciting the composite repair within the repair zone using a
21 broadband acoustic excitation signal, and receiving and analysing acoustic data from the
22 first acoustic scan to determine at least one approximate location of one or more defects in
23 the repair zone;

24 - in a second acoustic scan, exciting the composite repair in the at least one approximate
25 location using an acoustic excitation signal with frequency characteristics selected to
26 excite the composite material in preference to the metal substrate, and receiving and
27 analysing acoustic data from the second acoustic scan to enable the one or more defects
28 to be characterised as being present in the least one layer of a composite material or
29 present in the metal substrate.

30

31 The broadband acoustic excitation signal may comprise multiple frequencies in the range
32 of 1 kHz to 100 kHz. In a preferred embodiment, the broadband acoustic excitation pulse
33 may comprise multiple frequencies in the range of 5 kHz to 50 kHz, and may comprise a
34 spread of frequencies across that range. The inventor has appreciated that such
35 frequency ranges are effective for the inspection of composite repairs.

1 In the second acoustic scan, characterising the one or more defects as being present in
2 the least one layer of the composite material may include characterising a defect as being
3 internal to the composite material or being present at the interface of the composite layer
4 and the metal substrate (i.e. "in at least one layer of the composite material" is intended to
5 include "at the interface between the composite layer and the metal substrate").

6

7 The metal substrate may for example be a metal wall of a pressure vessel, such as a
8 pipeline wall, or may be a metal wall or component of another load bearing structure.

9

10 The second acoustic scan may have an acoustic excitation signal with a frequency in the
11 range of 10 kHz to 25 kHz. In another embodiment, the second acoustic scan may have
12 an acoustic excitation signal with a frequency in the range of 15 kHz to 20 kHz. In a
13 preferred embodiment, the second acoustic scan may have an acoustic excitation signal
14 with a frequency of approximately 17kHz (i.e. in the range 17kHz +/- 0.5kHz).

15

16 The method may comprise utilising an acoustic probe assembly comprising a transmitter
17 transducer and a receiver transducer. The method may comprise utilising a pitch and
18 catch acoustic method. The method may comprise manually operating an acoustic probe
19 assembly.

20

21 The method may comprise determining an approximate location of a defect using a first
22 acoustic probe assembly having wide field of view characteristics. The method may
23 comprise determining a location of a defect previously approximately located using a
24 second acoustic probe assembly having high spatial resolution characteristics.

25

26 The method may comprise sizing an identified defect. Sizing the identified defect may
27 comprise determining an excitation frequency at which the defect gives a maximum signal
28 response, and determining the extremities of the defect using a half amplitude analysis
29 method.

30

31 The method may comprise detecting a defect that has a dimension in a direction parallel to
32 the surface of the composite repair of less than 50mm. The method may comprise
33 detecting a defect that has a dimension in a direction parallel to the surface of the
34 composite repair of less than 30mm. The method may comprise detecting a defect that
35 has a dimension in a direction parallel to the surface of the composite repair of less than

1 20mm. The method may comprise detecting a defect that has a dimension in a direction
2 parallel to the surface of the composite repair of approximately 15mm.

3

4 The method may comprise detecting a defect that has a dimension in a direction normal to
5 the surface of the composite repair of less than 0.5mm. The method may comprise
6 detecting a defect that has a dimension in a direction normal to the surface of the
7 composite repair of less than 0.1mm. The method may comprise detecting a defect that
8 has a dimension in a direction normal to the surface of the composite repair of
9 approximately 0.05mm. This facilitates detection of kissing bonds and/or intra-layer
10 delaminations that have a much smaller dimension than those capable of being detected
11 using conventional techniques. This is particularly important for in-service inspection
12 methods, in which structures, vessels and/or pipelines being inspected may be at elevated
13 temperatures. At elevated operating temperatures, thermally induced expansion of metal
14 substrates may reduce the effective size of kissing bond defects to the point that they are
15 not detectable using less sensitive systems. An increased sensitivity to defect thickness in
16 a direction normal to the repair surface enables detection of smaller kissing bond defects,
17 and/or kissing bond defects that have been temporarily reduced in apparent thickness due
18 to the thermal conditions. This may be of particular importance in the inspection of
19 composite repairs on metal walls of pipelines in the oil and gas sector, which are
20 commonly used to carry fluids at elevated temperature.

21

22 The method may comprise characterising a depth of a defect in a direction normal to the
23 surface of the composite repair. Characterising the depth may comprise comparing an
24 acoustic response with an acoustic response of one or more reference samples having
25 defects of known depths. The method may comprise utilising a resonance probe method
26 to characterise a depth of a defect. The method may comprise utilising an MIA probe
27 method to characterise a depth of a defect.

28

29 The method may comprise manually manoeuvring the probe assembly in relation to the
30 structure.

31

32 The method may comprise carrying out acoustic inspection whilst the structure is at an
33 elevated temperature above an ambient temperature.

34

1 The method may comprise acoustic inspection, wherein the structure comprises a
2 substrate of steel or a steel alloy, and the composite material forms at least a part of a
3 composite repair applied to the substrate. The structure may comprise a pipeline, pipework
4 or a pressure containing vessel.

5

6 In an alternative embodiment, the structure may comprise a substrate of an alloy of nickel
7 and copper, or Monel® alloys, and the composite material forms at least part of a
8 composite repair applied to the substrate.

9

10 According to a second aspect of the invention, there is provided an apparatus for
11 acoustically inspecting a structure comprising a composite material, the apparatus
12 comprising:

13 a probe assembly comprising a housing and first and second acoustic transducer
14 subassemblies arranged in the housing;

15 wherein the first and second acoustic transducer subassemblies are configured to enable
16 operation as a transmitter and a receiver respectively;

17 wherein each of the transducer subassemblies is elongated along a respective axis of
18 orientation, has a first end configured to contact against a material to be inspected, and is
19 axially movable within a respective bore of the housing;

20 wherein the first ends of the first and second transducer subassemblies are biased
21 towards an extended position in a direction towards the first ends;

22 and wherein the axes of the first and second transducer subassemblies are inclined
23 towards one another.

24

25 The axes of the first and second transducer subassemblies are inclined towards one
26 another in a direction towards the first ends. The axes may converge at a point extending
27 from the first ends.

28

29 The angle between the axes of the two transducer subassemblies may be in the range of
30 10 degrees to 170 degrees. In another embodiment, the angle between the axes of the
31 two transducer subassemblies may be in the range of 30 degrees to 90 degrees. In a
32 preferred embodiment, the angle between the axes of the two transducer subassemblies
33 may be 60 degrees.

34

1 The housing may have a housing axis which in normal use is substantially perpendicular to
2 a surface of the material to be inspected.

3

4 An angle between the axis of the first transducer subassembly and the housing axis may
5 be approximately equal to an angle between the axis of the second transducer
6 subassembly and the housing axis. That is, the respective axes of the first and second
7 transducer assemblies may be oriented symmetrically about the housing axis.

8

9 In an alternative embodiment, the angles between the respective axes of the first and
10 second transducer subassemblies may be different from one another, and the respective
11 axes of the first and second transducer assemblies may be oriented asymmetrically about
12 the housing axis.

13

14 The axis of the first transducer subassembly or the axis of the second transducer
15 subassembly may be substantially parallel to the housing axis.

16

17 When the first and second transducer subassemblies are in their retracted positions, the
18 distance between the first ends of the first and second transducer subassemblies may be
19 in the range of 2mm to 12mm. In another embodiment, when in this retracted position, the
20 distance between the first ends of the first and second transducer subassemblies may be
21 in the range of 5mm to 9mm. In a preferred embodiment, when in this retracted position,
22 the distance between the first ends of the first and second transducer subassemblies may
23 be 7mm.

24

25 The housing may be manufactured from a low friction material. In a preferred embodiment
26 the housing may be manufactured from a polytetrafluoroethylene (PTFE)-based material.

27

28 The apparatus may comprise two or more wear pin elements, which may be provided on
29 the probe housing. The wear pins may provide a limit to the force that can be applied to
30 the first ends of the first and second transducer subassemblies when contacting with the
31 material to be inspected.

32

33 The apparatus may comprise a biasing means which biases the first and second
34 transducer subassemblies towards an extended position. At the retracted position, the
35 biasing means may exert a force component on each respective transducer

1 subassemblies in the range of 0.4 N to 1.5 N, measured on an axis bisecting the angle
2 between the transducer subassembly axes. In other words, a force on the probe assembly
3 in the range of 0.8 N to 3 N is required to act against the biasing means to retract both
4 transducer subassemblies to the retracted position, and the perpendicular force
5 component from each respective transducer subassemblies acting on the inspection
6 surface is in the range of 0.4 N to 1.5 N. Preferably, the same force is in the range of 0.7 N
7 to 1.1 N, and may be approximately 0.9 N. The retracted position may be a position at
8 which the wear pins (if present) are in contact with a surface of the material to be
9 inspected.

10

11 The biasing means may comprise a spring which maintains the first and second
12 transducer subassemblies biased towards an extended position within their respective
13 bores. The biasing means may comprise a pair of springs, each acting on a respective
14 transducer subassembly. Each spring may have a spring constant in the range of 0.15
15 N/mm (150 Nm^{-1}) to 0.25 N/mm (250 Nm^{-1}). In a preferred embodiment this spring
16 constant may be approximately 0.2 N/mm (200 Nm^{-1}).

17

18 Embodiments of the second aspect of the invention may include one or more features of
19 the first aspect of the invention or its embodiments, or vice versa.

20

21 According to a third aspect of the invention, there is provided a method of acoustically
22 inspecting a structure comprising a composite material, the method comprising using the
23 apparatus of the second aspect of the invention.

24

25 The method may comprise carrying out an acoustic scan of the structure by manually
26 manoeuvring the probe assembly in relation to the structure.

27

28 The method may comprise carrying out acoustic inspection whilst the structure is at an
29 elevated temperature above an ambient temperature.

30

31 The structure comprises a substrate of steel or a steel alloy, and the composite material
32 may form at least a part of a composite repair applied to the substrate. The structure may
33 comprise a pipeline, pipework or a pressure containing vessel.

34

1 In an alternative embodiment, the structure may comprise a substrate of an alloy of nickel
2 and copper, or Monel® alloys, and the composite material may form at least part of a
3 composite repair applied to the substrate.

4

5 Embodiments of the third aspect of the invention may include one or more features of the
6 first or second aspects of the invention or their embodiments, or vice versa.

7

8 Brief description of the drawings

9

10 There will now be described, by way of example only, embodiments of the invention with
11 reference to the following drawings, of which:

12

13 Figure 1A is a schematic representation of an acoustic inspection system according to an
14 embodiment of the invention;

15

16 Figure 1B is an enlarged sectional view a composite repair in the system of Figure 1A;

17

18 Figure 2 is a schematic representation of a method of acoustically inspecting a composite
19 repair on a pipeline according to an embodiment of the invention.

20

21 Figures 3A and 3B are schematic representations of an acoustic probe assembly used
22 with an embodiment of the invention;

23

24 Figures 4A to 4C are schematic representations of an alternative acoustic probe assembly
25 according to an embodiment of the invention;

26

27 Figure 5 is a schematic representation of additional method steps that may be used with
28 the method of Figure 2;

29

30 Figure 6 is a schematic representation of additional method steps that may be used with
31 the method of Figure 2;

32

33 Figure 7 is a schematic representation of additional method steps that may be used with
34 the method of Figure 2;

35

1 Figure 8 is a schematic representation of a method of acoustically inspecting a composite
2 repair according to a particular embodiment.

3

4 Detailed description of preferred embodiments

5

6 Embodiments of the invention will be described in the context of the inspection of
7 composite repairs on pipework, by way of example only, and it will be appreciated that the
8 invention in at least some of its aspects is applicable to the inspection of composite repairs
9 on other kinds of load-bearing structures, including pressure vessels and pipelines formed
10 from a metal substrate, and in particular structures formed from steel or alloys of steel,
11 including but not limited to mild steel, stainless steel, super duplex steel, duplex steel and
12 cunifer.

13

14 Referring firstly to Figures 1A and 1B, there is shown a system 100 comprising a pipeline
15 101 and an acoustic inspection system 102. The pipeline is formed from multiple sections,
16 including linear pipe joints 104 and an elbow joint 106 connected to the linear joints 104 by
17 flanges. The pipe joints and elbow joint are formed from a steel alloy selected according
18 to the operating conditions of the pipeline, and define a pipe wall.

19

20 The elbow joint 106 has been subject to a composite repair, according to techniques
21 known in the industry, and has a laminated structure 108 formed from multiple layers of
22 composite material applied around the steel of the elbow joint 106. The composite
23 material is applied in a repair zone and maintains and/or re-establishes the pressure
24 bearing capability of the pipe at the elbow joint 106. The structure 108 follows the
25 geometry of the elbow joint, which in this case is a 90 degree elbow.

26

27 The acoustic inspection system 102 comprises a probe assembly 120 connected to a
28 control unit 124 by a cable 122. The probe assembly 120 is manually operable and
29 manoeuvrable in relation to the inspection target, and as such can be readily positioned
30 with respect to parts of the inspection target required to be inspected in a range of
31 orientations, without a requirement for a specific mounting or tracking systems that define
32 the probe-target geometry. This makes the probe suitable for targets with a wide range of
33 shapes and geometries (including the elbow joint shown in the example). The probe
34 assembly 120 is a "pitch and catch" probe assembly, comprising a transmitter acoustic

1 transducer subassembly and a receiver acoustic transducer subassembly, as will be
2 described in more detail below.

3

4 A perceived drawback of using composite repair techniques on a metal base pipe or other
5 metal substrate is that inspection methods typically used in the industry to inspect the
6 integrity of the pipes are not applicable, or at least have limited applicability. Defects and
7 flaws in the substrate materials may be more difficult to detect due the material in the
8 repair zone not being directly accessible by inspection instruments. In addition, the
9 composite repair structure itself may have defects or flaws within the structure of the
10 composite material (e.g. between laminations) and/or at the composite-metal interface,
11 such as kissing bond defects.

12

13 Figure 1B is a schematic cross section through a part of the elbow joint 106 in the repair
14 zone, showing representative defects in the steel wall of the joint 106 and in the composite
15 material structure 108. In the representation of Figure 1B, the repaired elbow joint
16 comprises a kissing bond defect 112 (or unbonding/delamination of the composite and the
17 substrate), composite material internal defects 114a and 114b, a wall thickness loss defect
18 116 on the internal surface of the joint, a surface pitted defect 118, and a crack 119. In the
19 context of this specification, defects or flaws outside of the outer surface 107 of the wall of
20 the elbow joint (or other substrates where applicable) are considered to be “in the
21 composite”, whereas defects inside of the outer surface of the wall are considered to be “in
22 the wall”. Defects 112, 114a, and 114b are therefore characterised as in the composite
23 material, whereas defects 116, 118 and 119 are considered to be in the wall. It is a
24 feature of aspects of the invention that such defects can be located and characterised as
25 being in the composite structure or in the wall, as will be described below.

26

27 Figure 2 is a schematic representation of a method of acoustically inspecting a composite
28 repair on a pipeline according to an embodiment of the invention. The method, generally
29 shown at 200, comprises a first step 201 of carrying out a first acoustic scan by exciting
30 the pipeline in a repair zone using a broadband acoustic pulse from the probe assembly
31 120, by placing the probe assembly into physical contact with an outer surface of the
32 composite structure 108, and moving the probe assembly over the surface. The frequency
33 and amplitude characteristics of the broadband acoustic pulse are set by the control unit
34 124, and in a preferred embodiment of the invention, the pulse is a low frequency
35 broadband acoustic pulse with frequencies from 5kHz to 50kHz. Other low frequency

1 broadband acoustic pulses may be used in other preferred embodiments of the invention,
2 for example with frequencies between 1kHz to 100kHz. In general, the inventor has
3 identified that acoustic pulses with frequencies below 100kHz, and preferably below
4 50kHz, are most suitable for the inspection of composite repairs.

5

6 The probe assembly 120 of this embodiment is a “pitch and catch” probe assembly,
7 comprising a transmitter acoustic transducer subassembly and a receiver acoustic
8 transducer subassembly. The acoustic data from the excited inspection area is received
9 by the probe assembly (step 203) and transmitted to the control unit 124. The control unit
10 124 comprises a display element which displays information to the operator of the probe
11 assembly in real time, facilitating the scanning operation.

12

13 Analysis of the received data (step 205) is carried out, at least in part, by the operator of
14 the probe in as the scan is performed. Alternatively, or in addition, data received by the
15 probe is transmitted to a connected data analysis module, which may be for example a
16 computer running suitable data analysis software. Optionally the data are digitally
17 recorded, and may be processed and/or analysed by the data analysis module to assist,
18 enhance or replace real-time analysis performed by the operator.

19

20 A purpose of the analysis is to locate, at least approximately, the position of one or more
21 defects in the composite repair. The defects may include (without limitation) kissing bond
22 defects (or unbonding/delamination of the composite and the substrate), composite
23 material internal defects, wall thickness loss defects on the internal surface of the joint,
24 surface pitted defects, and/or cracks. Through assessment of acoustic waveform
25 responses by the operator or by analysis software (or a combination of the two), the
26 presence of a defect is identified and its location or approximate location over the surface
27 of the repair zone is recorded (step 207). Using this approach, defects can be located with
28 an accuracy of around +/- 20mm, in a direction parallel to the surface of the composite
29 repair. Recording the location may be facilitated by applying a grid pattern to the surface
30 of the repair zone and recording a corresponding grid reference, using x and y co-
31 ordinates where the x axis is the longitudinal direction of the pipe, and the y axis is a
32 circumferential direction around the pipe.

33

34 Although the first broadband scan enables location of a defect over the surface of the
35 repair zone in the x-y directions, in most cases it is not possible to determine where the

1 defect is in a z-axis, corresponding to a radial depth below the surface in the combined
2 volume of composite material and substrate. The method includes a second acoustic scan
3 at a frequency or frequencies selected to excite the composite material in preference to
4 the excitation of the substrate. In many typical pressure vessel applications, where the
5 substrate is formed from a steel-based material, it has been observed by the inventor that
6 an acoustic pulse of approximately 17kHz does not excite a steel material sufficiently to be
7 sensitive to defects located in the substrate. For example, a scan with an acoustic pulse
8 of 17kHz would not detect the defects 116, 118 or 119 of Figure 1B, but would detect
9 defects 112, 114a and 114b in the composite structure.

10

11 Applying this phenomenon in the method, a second acoustic scan excites the composite
12 repair at a frequency of 17kHz (step 209), in the previously determined x-y location or
13 approximate location from step 207. Acoustic data is received (211) from the excited
14 composite material and is analysed (213). Through assessment of acoustic waveform
15 responses by the operator or by analysis software (or a combination of the two), an
16 approximate location in the z-direction can be determined. If the presence of a defect is
17 identified, it can be noted that there is a defect present in the composite material (including
18 being a kissing bond defect or unbonding between the composite and the substrate at
19 interface 107). If no defect is identified in the second scan, the location from 207 can be
20 recorded as a location of a defect in the steel substrate. The method has therefore been
21 used to determine whether there is a defect at a particular location in the x-y surface, and
22 its approximate location in the z-direction (i.e. whether it is present in the composite repair
23 material). Various additional steps to further characterise the defect can optionally be
24 taken as indicated by the arrows 217 and described in more detail below.

25

26 In the method 200, an approximate location of the defect can be determined by the steps
27 201 to 207 using a pitch and catch probe assembly 120a as described with reference to
28 Figures 3A and 3B. The probe assembly 120a comprises a pair of transducer
29 subassemblies 131a, 131b mounted in bores 132a, 132b in a probe housing 133. The
30 transducer subassemblies 131 are movable in the bores 132 along their respective axes
31 138 between an extended outer position (Figure 3A) and a retracted inner position (Figure
32 3B), and are biased towards their outer positions by respective springs 134. The
33 transducer subassemblies have contact tips 135, which are configured to be placed into
34 contact with an inspection target to acoustically couple the transducer assemblies to the
35 inspection target without use of coupling media such as gels or liquids. In use, an operator

1 pushes the contact tips against the outer surface of the composite repair to at least
2 partially retract the transducer subassemblies into the probe housing. Wear pins 136
3 provided on the surface of the housing prevent retraction of the subassemblies beyond a
4 defined position and reduce damage to the housing and transducer subassemblies during
5 use. The probe assembly 120a can be moved over the composite repair surface, and the
6 biased axial movement of the subassemblies enables the contact tips 135 to ride over
7 undulations and rough sections of the composite while still remaining in physical contact
8 for acoustic coupling.

9

10 The force of the springs is selected to exert an appropriate force on the transducer
11 subassemblies at the operative position (i.e. retracted to the point at which the wear pins
12 contact the inspection material surface). A typical force component on each transducer
13 subassembly is in the range of 0.4 N to 1.5 N, measured on an axis bisecting the angle
14 between the transducer subassembly axes. As there are two subassemblies with
15 respective springs, the force on the probe assembly in the range of 0.8 N to 3 N is required
16 retract both transducer subassemblies to the operative position. In a particular
17 embodiment, the force from each transducer subassembly on the inspection surface is
18 approximately 0.9 N. Each spring may have a spring constant of approximately 0.2 N/mm
19 (200 Nm^{-1}).

20

21 In the probe assembly 120a, the transducer subassemblies are mounted parallel to one
22 another and in use are applied substantially perpendicularly to the surface of the
23 composite in the repair zone. Such a probe set up provides a relatively wide field of view
24 during the scan, which is useful for initial and approximate location of defects in the x-y
25 directions. However, the spatial resolution of defect location in the x-y direction is
26 compromised, and in particular embodiments of the invention, a novel probe assembly
27 may be used for some of the inspection steps. Spacing between the contact tips 135 may
28 be within a range of approximately 2mm to 20mm, and is selected depending on factors
29 including the thickness of the composite repair layers, and the required sensitivity to near
30 and/or far wall defects. A spacing approaching 2mm will have increased sensitivity to
31 defects at very near surface, while a spacing approaching 20mm will cause a loss of near
32 surface sensitivity but increase far wall sensitivity. A spacing of approximately 10mm is
33 typical.

34

1 Figure 4A is a perspective view of a probe assembly 120b according to an embodiment of
2 the invention. Figures 4B and 4C are part-sectional views of the probe assembly 120b in
3 extended and retracted conditions respectively. The probe assembly 120b is similar to
4 probe assembly 120a, with like features indicated by like reference numerals incremented
5 by 10. The probe assembly 120b differs from the probe assembly 120a in that the
6 orientation axes of the transducer subassemblies 141 are inclined to one another in a
7 direction towards the contact tips 145. In use, an operator pushes the contact tips 145
8 against the outer surface of the composite repair to partially retract the transducer
9 subassemblies into the bores 142a, 142b of probe housing 143 along the axes 148. Wear
10 pins 146 limit retraction of the subassemblies to a defined position, shown in Figure 4C. In
11 this position, the contact tips of the transducer subassemblies are at a defined spacing
12 from one another.

13

14 The probe assembly 120b can be moved over the composite repair surface, and the
15 biased axial movement of the assemblies enables the contact tips 145 to ride over
16 undulations and rough sections of the composite while still remaining in physical contact
17 for acoustic coupling. The inclined axes of the subassemblies 142 means that the
18 retraction forces acting on the subassemblies from the surface of the inspection target are
19 not directed substantially along the direction of the bores and the subassembly axes, as
20 they would typically be in the probe assembly 120a. To facilitate smooth movement of the
21 transducer subassemblies in the bores, the housing 143 of this embodiment is formed
22 from a low friction material. In this case, the housing is formed from a material which has
23 sufficient wear characteristics, low friction properties, and does not resonate in the
24 acoustic frequency ranges used in the inspection methods. An example category of such
25 materials are self-lubricating composite materials comprising resin and
26 polytetrafluoroethylene (PTFE), an example of which is the composite material marketed
27 as TUF COT® T200P by Tufcot Engineering Ltd. Other materials, including low friction
28 and/or self-lubricating polymers or composites may be used in other embodiments of the
29 invention. In alternative embodiments, rather than forming the housing from a low friction
30 material, the transducer subassemblies and/or the wall of the bore may be formed from or
31 coated with a low friction material to facilitate smooth movement of the transducer
32 subassemblies in the housing.

33

34 The inventor has identified that certain geometries of probe assembly, and in particular the
35 angle of the transducer subassembly transducer axes and the spacing between contact

1 tips, are beneficial for improved acoustic inspection of composite repairs. In the
2 embodiment of Figure 4, the internal angle between the respective axes of the transmitter
3 transducer and the receiver transducer is 60 degrees, and the wear pins 146 define a
4 retracted position of the transducers with a spacing of 7mm. This geometry has been
5 found by the inventor to improve the spatial resolution of defects, in terms of position and
6 sizing, in the x-y direction, compared with a configuration with parallel probe orientation as
7 in probe assembly 120a. In addition, the geometry of the transducers in probe assembly
8 120b has been found to enable the detection of near surface defects in the composite
9 material (i.e. those at shallow depths beneath the outer surface of the composite), that
10 could not be detected with the probe assembly 120a. In particular, the probe assembly
11 120b has successfully detected defects at depths as low as 0.8mm below the outer
12 surface of the composite, which is equivalent to approximately one layer of the composite
13 wrap. In comparison to this, the minimum depth of defects detectable by conventional
14 techniques is typically 25mm below the outer surface of the composite. With respect to
15 the x-y dimension of defects, the probe assembly 120b has successfully detected defects
16 with a dimension of less than 20mm, and even defects with an x-y dimension as low as
17 approximately 15mm.

18
19 Variations to the geometry of the probe assembly 120b have also been found to offer
20 beneficial results in locating defects in the x-y direction, detecting defects with small
21 dimensions in the x-y direction, and/or detection of near surface defects. Internal angles
22 between the respective axes of the transmitter transducer and the receiver transducer in a
23 range of 30 degrees to 90 degrees, and more preferably in the range of 45 degrees to 75
24 degrees, have been found to be advantageous. Contact tip spacings at the retracted
25 position in the range of 3mm to 11mm, and more preferably in the range of 5mm to 9mm,
26 have been found to be advantageous.

27
28 Although the probe assembly 120b is shown as having the transmitter transducer and the
29 receiver transducer at approximately equal angles to a housing axis which in normal use is
30 substantially perpendicular to a surface of the material to be inspected, alternative
31 configurations are within the scope of the invention. For example, the transmitter
32 transducer may be parallel to the housing axis, whilst the receiver transducer is at an
33 angle to the housing axis. In a further alternative embodiment, the receiver transducer may
34 instead be parallel to the housing axis, whilst the transmitter transducer is at an angle to
35 the housing axis. In a further alternative embodiment, the transmitter and receiver

1 transducer may be positioned such that they are each at a different angle to the housing
2 axis.

3

4 As described above, inclined transducer axes have benefits in terms of sensitivity to
5 defects, but offer a narrower field of view and therefore may not be suitable for initial scans
6 of large surfaces. Accordingly, methods of embodiments of the invention may include
7 multiple scans with different probe assemblies. For example, scans can be performed
8 using a probe assembly 120a (i.e. with parallel transducer axes) to approximately locate
9 defects in the x-y direction. Subsequent scans can be performed using a probe assembly
10 with inclined transducer axes (e.g. probe assembly 120b) in particular locations in which
11 defects have been approximately located using probe 120a.

12

13 Figures 5 to 7 are schematic representations of additional method steps that may be used
14 with the method 200 to enhance or improve the inspection results.

15

16 Referring to Figure 5, there is shown generally at 500 a group of method steps that may be
17 performed to determine the size of a defect in a composite repair. At step 501, an
18 approximate location in an x-y direction has been determined using a broadband excitation
19 and data analysis method as described with reference to Figure 2, steps 201 to 207.

20 Optionally, the steps 201 to 207 are repeated using a probe with inclined transducer axes
21 (e.g. probe assembly 120b) to more accurately determine the location of the defect.

22 Having determined the location, the operator selects a particular frequency and inspects
23 the defect (step 503), analysing the response (505). This is repeated (loop 504) for a
24 number of different frequencies until the operator has determined an optimal frequency
25 that maximises the response amplitude for the defect inspected (step 507). At this optimal
26 frequency, a "half-amplitude" method is performed (509); the extremities of the half-
27 amplitude signal in the x and y directions are recorded to characterise the size of the
28 defect (step 511).

29

30 The steps 500 may be performed in addition to the steps of method 200, at any point after
31 a defect has been approximately located or located in the composite repair zone.

32

33 Referring to Figure 6, there is shown generally at 600 a group of method steps that may be
34 performed to determine a depth (location in the z-direction) of a defect in a composite
35 repair. At step 601, an approximate depth in the z-direction (i.e. whether the defect is in

1 the composite material) has been determined using the selective frequency excitation and
2 data analysis method as described with reference to Figure 2, steps 209 to 215. At step
3 603, the operator uses a resonance probe at a specific frequency and compares the signal
4 and phase responses with signal and phase responses from reference samples at known
5 depths. Correlation between the signal and phase responses of the composite repair and
6 the reference sample enables the operator to characterise an accurate depth of the defect
7 (i.e. its position in the composite material). In this regard, “accurate depth” is used only as
8 a term relative to the “approximate depth” determination of steps 209 to 215 of method
9 200.

10

11 The steps 600 may be performed in addition to the steps of method 200, at any point after
12 a defect has been identified in the composite material.

13

14 Referring to Figure 7, there is shown generally at 700 a group of alternative method steps
15 that may be performed to determine a depth (location in the z-direction) of a defect in a
16 composite repair. The steps 700 may be performed instead of the method steps 600 of
17 Figure 6, for example if the resonance probe method does not identify a correlation with a
18 reference sample, or may be used in conjunction with the steps 600 for example to provide
19 verification.

20

21 At step 701, an approximate depth in the z-direction (i.e. whether the defect is in the
22 composite material) has been determined using the selective frequency excitation and
23 data analysis method as described with reference to Figure 2, steps 209 to 215. At step
24 703, the operator uses a mechanical impedance analysis (MIA) probe at a specific
25 frequency and compares the signal and phase responses with signal and phase
26 responses from reference samples at known depths. Correlation between the signal and
27 phase responses of the composite repair and the reference sample enables the operator
28 to characterise an accurate depth of the defect (i.e. its position in the composite material).

29

30 The steps 700 may be performed in addition to the steps of method 200, at any point after
31 a defect has been identified in the composite material.

32

33 Some or all of the groups of optional method steps 500, 600 and 700 may be performed in
34 conjunction with the method 200, and the groups may be performed in different orders
35 depending on operational requirements and convenience.

1

2 Figure 8 is a schematic representation of a method of acoustically inspecting a composite
3 repair according to a particular embodiment, in which the steps of the method 200 and
4 optional steps of Figures 5 to 7 are performed in a particular sequence. In the method,
5 generally depicted at 800, an approximate location of a defect in the x-y surface of the
6 composite repair is determined by the method steps 201 to 207 of Figure 2, using a probe
7 assembly 120a with parallel transducer axes (step 801). At 802, method steps 201 to 207
8 of Figure 2 are repeated with a probe assembly 120b, having inclined transducer axes, in
9 order to more accurately determine the location of the defect in the x-y surface of the
10 composite repair. The location being determined, the size of the defect is characterised
11 (step 803) by the steps 500 of Figure 5.

12

13 Step 804 determines an approximate depth of the defect (i.e. its location in the composite
14 material) by the steps 209 to 215 of Figure 2. A more accurate depth position is
15 determined by the resonance probe (step 805) using method steps 600 of Figure 6, and/or
16 by the MIA probe (step 806) using method steps 700 of Figure 7.

17

18 The invention provides a method and apparatus for acoustically inspecting a composite
19 repair on a metal structure, the composite repair comprising at least one layer of a
20 composite material applied to a metal substrate of the structure in a repair zone. The
21 method comprises exciting the composite repair within the repair zone using a broadband
22 acoustic excitation signal, and receiving and analysing acoustic data from the first acoustic
23 scan to determine at least one approximate location of one or more defects in the repair
24 zone. In a second acoustic scan, the composite repair is excited in the at least one
25 approximate location using an acoustic excitation signal with frequency characteristics
26 selected to excite the composite material in preference to the metal substrate, and
27 receiving and analysing acoustic data from the second acoustic scan to enable the one or
28 more defects to be characterised as being present in the least one layer of a composite
29 material or present in the metal substrate. In an aspect of the invention, an acoustic probe
30 assembly comprises a housing and first and second acoustic transducer subassemblies
31 arranged in the housing. The first and second acoustic transducer subassemblies are
32 configured to enable operation as a transmitter and a receiver respectively, and each of
33 the transducer subassemblies is elongated along a respective axis of orientation, has a
34 first end configured to contact against a material to be inspected, and is axially movable
35 within a respective bore of the housing. The first ends of the first and second transducer

1 subassemblies are biased towards an extended position in a direction towards the first
2 ends; and the axes of the first and second transducers are inclined towards one another.

3

4 The invention in its described embodiments enables in-service inspection and monitoring
5 of the structural integrity of composite repairs applied to structures, including vessels and
6 pipelines. The apparatus and method have improved sensitivity to defects and flaws of
7 small dimensions and an ability to be applied to a wide range of geometries. The
8 techniques enable detection of defects that have a smaller dimension in a direction normal
9 to the surface of the composite repair when compared with the prior art, which may be less
10 than 0.1mm and as low as approximately 0.05mm. This facilitates detection of kissing
11 bonds and/or intra-layer delaminations that have a much smaller dimension than those
12 capable of being detected using conventional techniques. This is particularly important for
13 in-service inspection methods, in which structures including vessels and/or pipelines being
14 inspected may be at elevated temperatures, at which the apparent size of the defect may
15 be reduced due to the thermal conditions. This may be of particular importance in the
16 inspection of composite repairs on metal pipelines in the oil and gas sector, which are
17 commonly used to carry fluids at elevated temperature.

18

19 Variations to the above-described embodiments fall within the scope of the invention as
20 claimed.

21

22

1 Claims

2

3 1. A method of acoustically inspecting a composite repair on a metal structure, the
4 composite repair comprising at least one layer of a composite material applied
5 to a metal substrate of the structure in a repair zone, wherein the method
6 comprises:

7 - in a first acoustic scan, exciting the composite repair within the repair zone
8 using a broadband acoustic excitation signal, and receiving and analysing
9 acoustic data from the first acoustic scan to determine at least one approximate
10 location of one or more defects in the repair zone;

11 - in a second acoustic scan, exciting the composite repair in the at least one
12 approximate location using an acoustic excitation signal with frequency
13 characteristics selected to excite the composite material in preference to the
14 metal substrate, and receiving and analysing acoustic data from the second
15 acoustic scan to enable the one or more defects to be characterised as being
16 present in the least one layer of a composite material or present in the metal
17 substrate.

18

19 2. The method according to claim 1, wherein the broadband acoustic excitation
20 signal comprises multiple frequencies in the range of 1 kHz to 100 kHz.

21

22 3. The method according to claim 2, wherein the broadband acoustic excitation
23 pulse comprises multiple frequencies in the range of 5 kHz to 50 kHz.

24

25 4. The method according to any preceding claim, wherein the second acoustic
26 scan has an acoustic excitation signal with a frequency in the range of 15 kHz to
27 20 kHz.

28

29 5. The method according to claim 4, wherein the second acoustic scan has an
30 acoustic excitation signal with a frequency of approximately 17kHz.

31

32

33 6. The method according to any preceding claim, wherein the method comprises
34 utilising an acoustic probe assembly comprising a transmitter transducer and a
35 receiver transducer.

36

- 1 7. The method according to claim 6, wherein the method comprises utilising a pitch
2 and catch acoustic method.
3
- 4 8. The method according to any preceding claim, wherein the approximate location
5 of a defect is detected using a first acoustic probe assembly having wide field of
6 view characteristics.
7
- 8 9. The method according to any preceding claim, comprising determining a
9 location of a defect that has been previously approximately located, using a
10 second acoustic probe assembly having high spatial resolution characteristics.
11
- 12 10. The method according to any preceding claim, comprising sizing an identified
13 defect using a half amplitude analysis method.
14
- 15 11. The method according to any preceding claim, comprising detecting a defect
16 that has a dimension in a direction normal to the surface of the composite repair
17 of less than 0.5mm.
18
- 19 12. The method according to any preceding claim, comprising characterising a
20 depth of a defect in a direction normal to the surface of the composite repair by
21 comparing an acoustic response with an acoustic response of one or more
22 reference samples having defects of known depths.
23
- 24 13. The method according to claim 12, wherein characterising a depth of a defect
25 utilises a method selected from a resonance probe method and an MIA probe
26 method.
27
- 28 14. The method according to any preceding claim, comprising carrying out an
29 acoustic scan of the structure by manually manoeuvring the probe assembly in
30 relation to the structure.
31
- 32 15. The method according to any preceding claim, wherein the structure is at an
33 elevated temperature above an ambient temperature during the acoustic
34 inspection.
35

- 1 16. The method according to any preceding claim, wherein the structure comprises
2 a substrate of steel or a steel alloy, and the composite material forms at least a
3 part of a composite repair applied to the substrate.
4
- 5 17. The method according to any preceding claim, wherein the structure comprises
6 a pipeline, pipework or a pressure containing vessel.
7
- 8 18. An apparatus for acoustically inspecting a structure comprising a composite
9 material, the apparatus comprising:
10 - a probe assembly comprising a housing and first and second acoustic
11 transducer subassemblies arranged in the housing;
12 - wherein the first and second acoustic transducer subassemblies are
13 configured to enable operation as a transmitter and a receiver
14 respectively;
15 - wherein each of the transducer subassemblies is elongated along a
16 respective axis of orientation, has a first end configured to contact
17 against a material to be inspected, and is axially movable within a
18 respective bore of the housing;
19 - wherein the first ends of the first and second transducer subassemblies
20 are biased towards an extended position in a direction towards the first
21 ends;
22 - and wherein the axes of the first and second transducer subassemblies
23 are inclined towards one another.
24
- 25 19. The apparatus according to claim 18, wherein the angle between the axes of the
26 two transducer subassemblies may be in the range of 30 degrees to 90
27 degrees.
28
- 29 20. The apparatus according to claim 19, wherein the angle between the axes of the
30 two transducer subassemblies is approximately 60 degrees.
31
- 32 21. The apparatus according to any of claims 18 to 20, wherein when the first and
33 second transducer subassemblies are in their retracted positions, the distance
34 between the first ends of the first and second transducer subassemblies is in the
35 range of 5mm to 9mm.

1

2 22. The apparatus according to claim 21, wherein when the first and second
3 transducer subassemblies are in their retracted positions, the distance between
4 the first ends of the first and second transducer subassemblies is 7mm.

5

6 23. The apparatus according to any of claims 18 to 22, wherein the housing
7 comprises a low friction material.

8

9 24. The apparatus according to claim 23, wherein the housing comprises a
10 polytetrafluoroethylene (PTFE)-based material.

11

12 25. The apparatus according to any of claims 18 to 24, wherein two or more wear
13 pins are provided on the probe housing.

14

15 26. The apparatus according to claim 25, wherein the wear pins provide a limit to
16 the force that can be applied to the first ends of the first and second transducer
17 subassemblies when contacting with the material to be inspected.

18

19 27. The apparatus according to claim 25 or claim 26 comprising a biasing means
20 which biases the first and second transducer subassemblies towards an
21 extended position, and wherein at the retracted position when the wear pins are
22 in contact with the material to be inspected, the biasing means exerts a force on
23 the respective transducer subassemblies in the range of 0.4 N to 1.5 N.

24

25 28. A method to acoustically inspect a structure comprising a composite material,
26 the method comprising using the apparatus of the any of claims 18 to 27.

27

28 29. The method according to claim 28, comprising carrying out an acoustic scan of
29 the structure by manually manoeuvring the probe assembly in relation to the
30 structure.

31

32 30. The method according to claim 28 or claim 29, wherein the structure is at an
33 elevated temperature above an ambient temperature during the acoustic
34 inspection.

35

- 1 31. The method according to any of claims 28 to 30, wherein the structure
2 comprises a substrate of steel or a steel alloy, and the composite material forms
3 at least a part of a composite repair applied to the substrate.
4
- 5 32. The method according to any of claims 28 to 31, wherein the structure
6 comprises a pipeline, pipework or a pressure containing vessel.
7
- 8 33. The method according to any of claims 1 to 17, using the apparatus according to
9 any of claims 18 to 27.
10

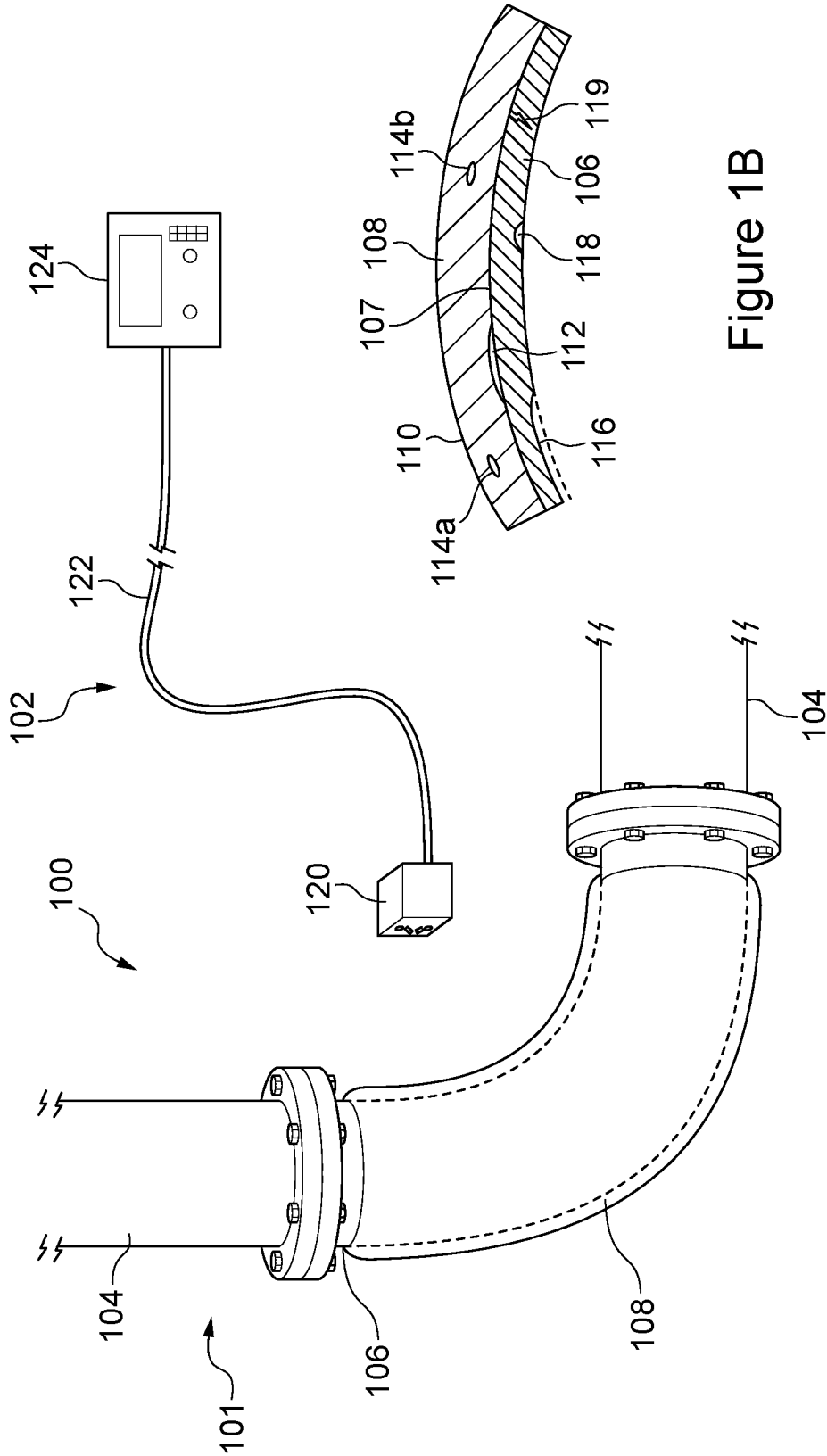


Figure 1B

Figure 1A

2/7

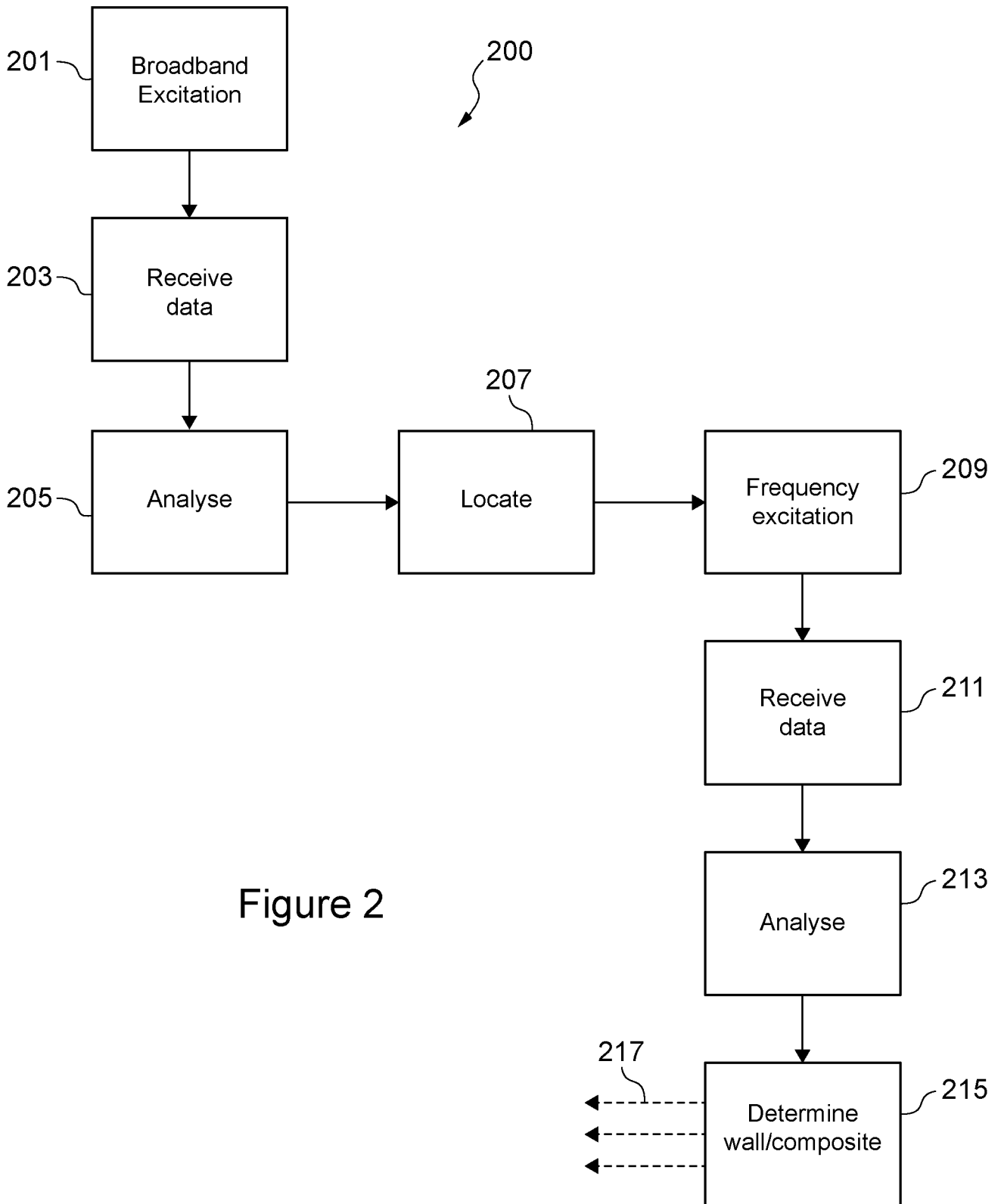


Figure 2

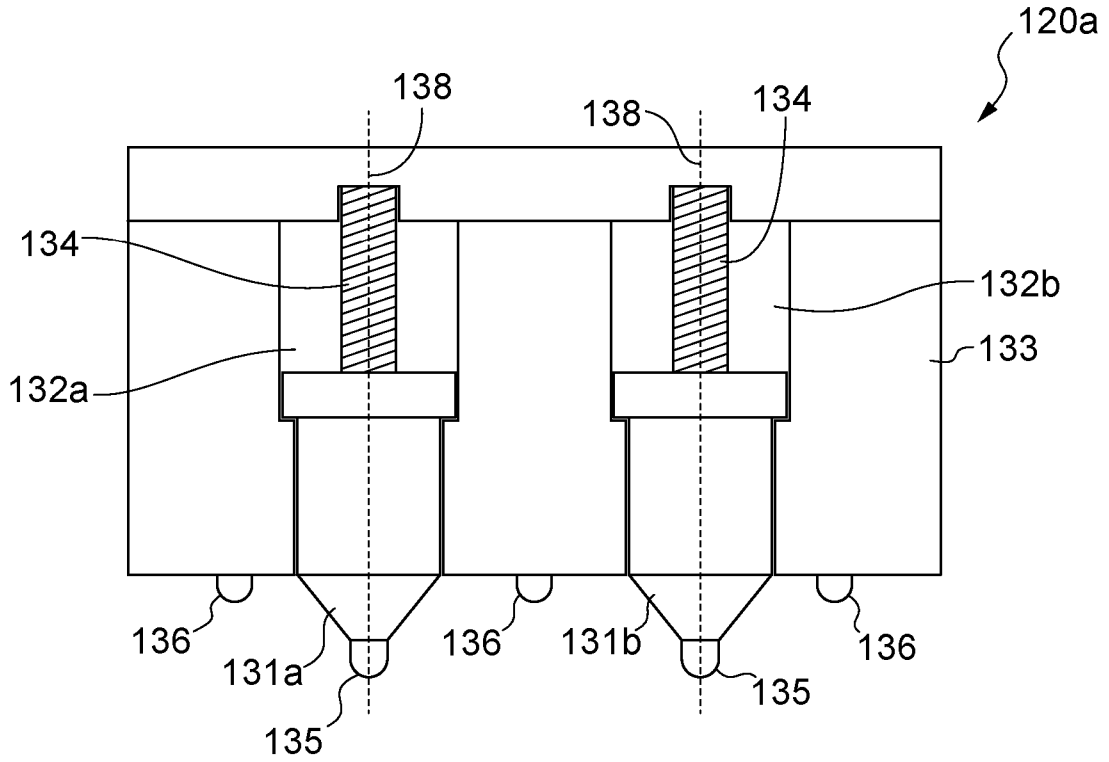


Figure 3A

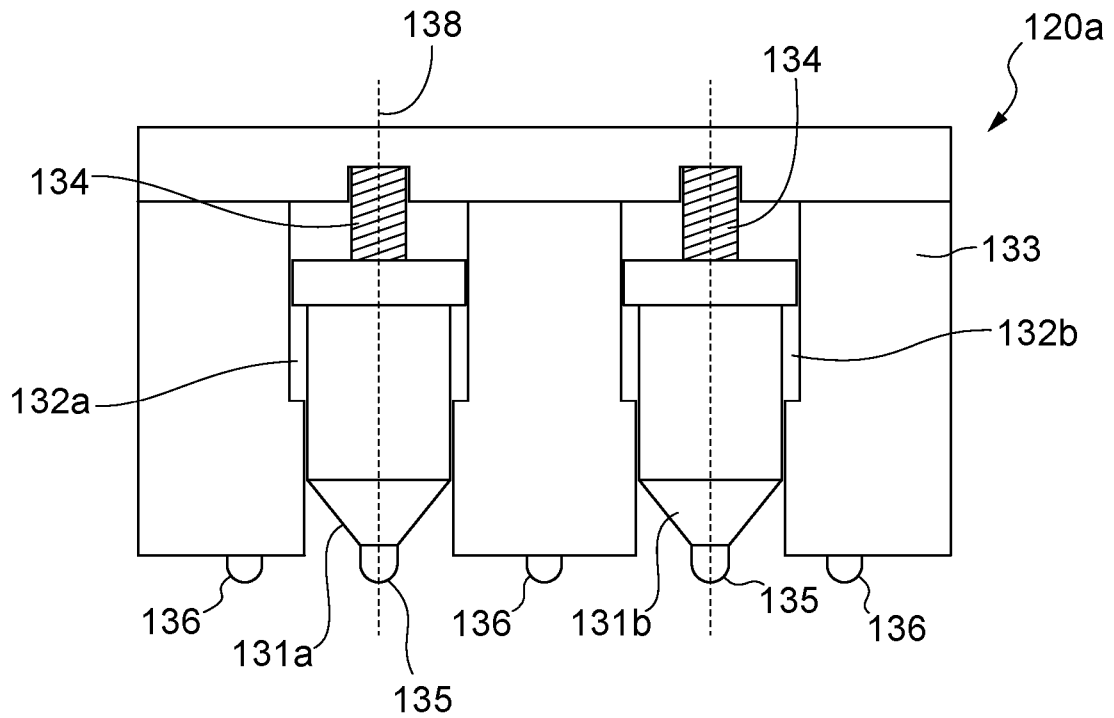


Figure 3B

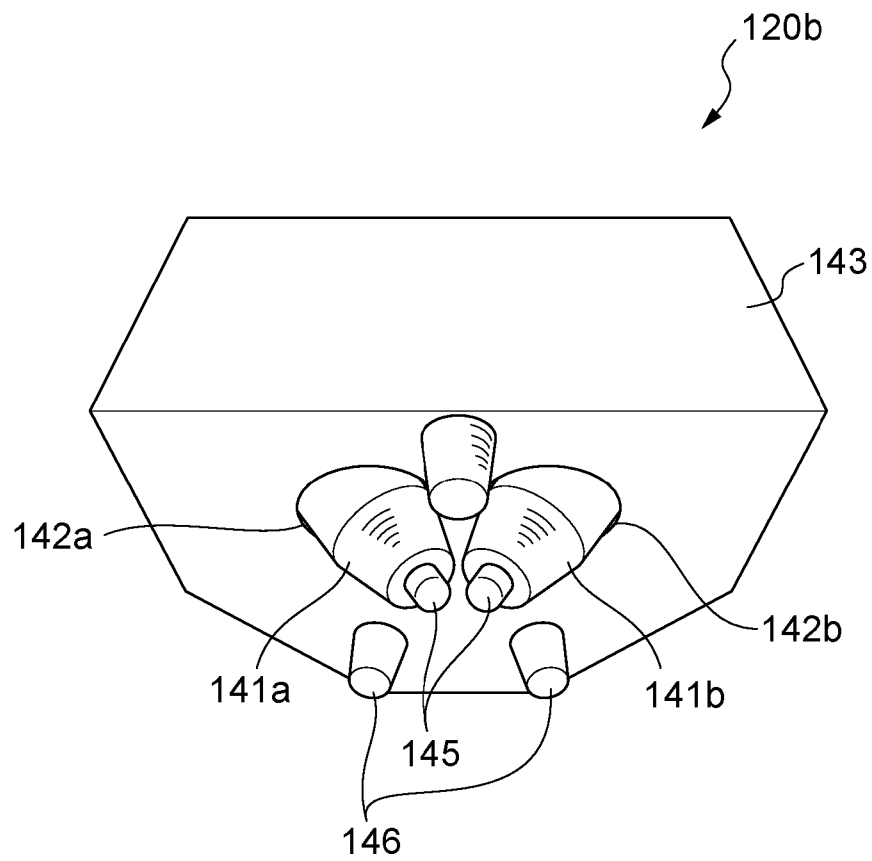


Figure 4A

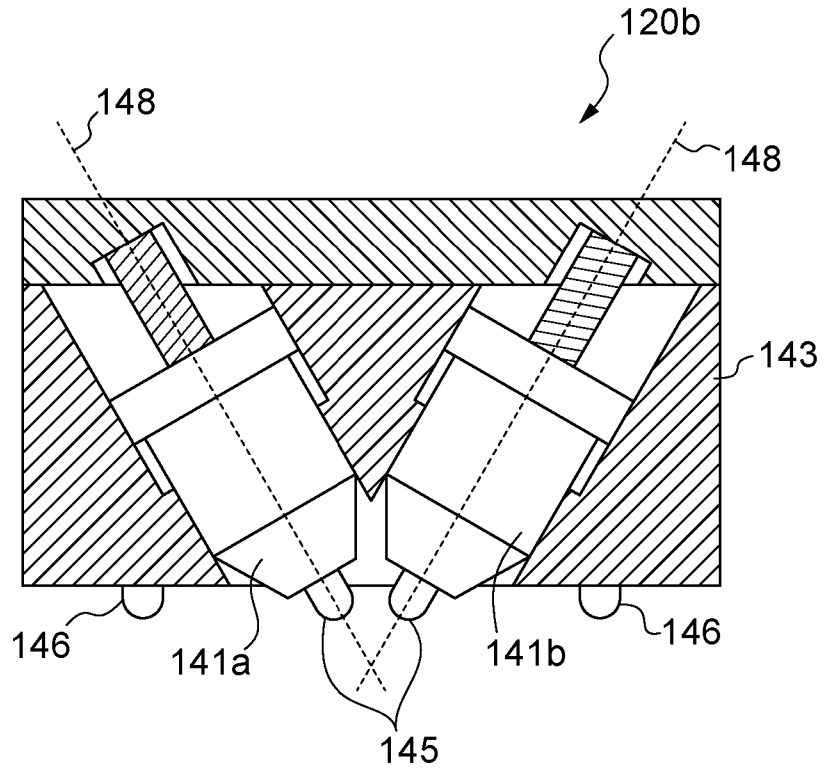


Figure 4C

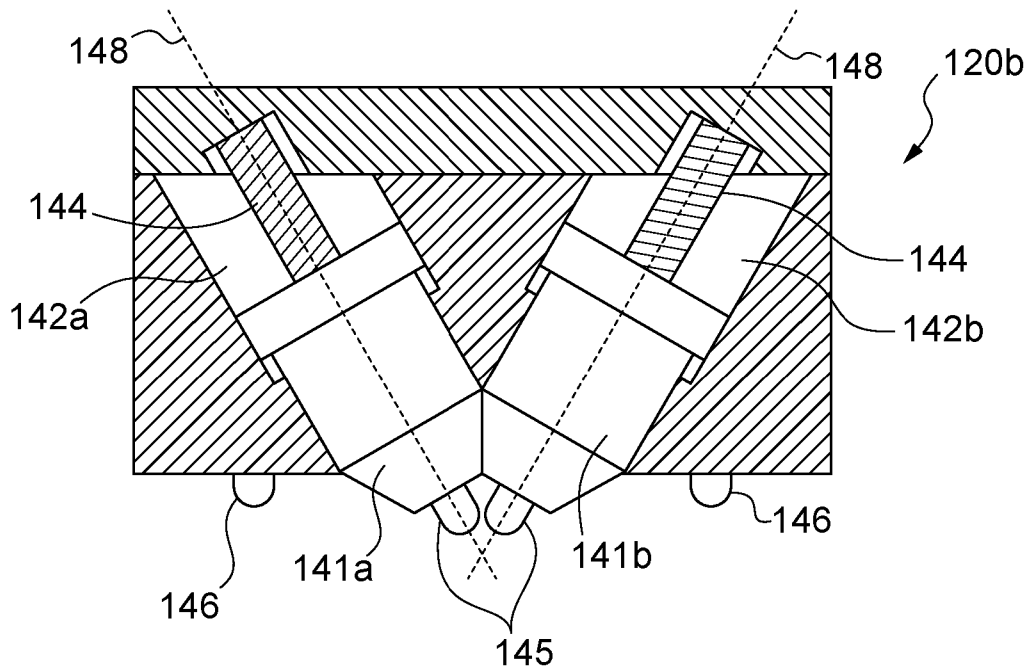


Figure 4B

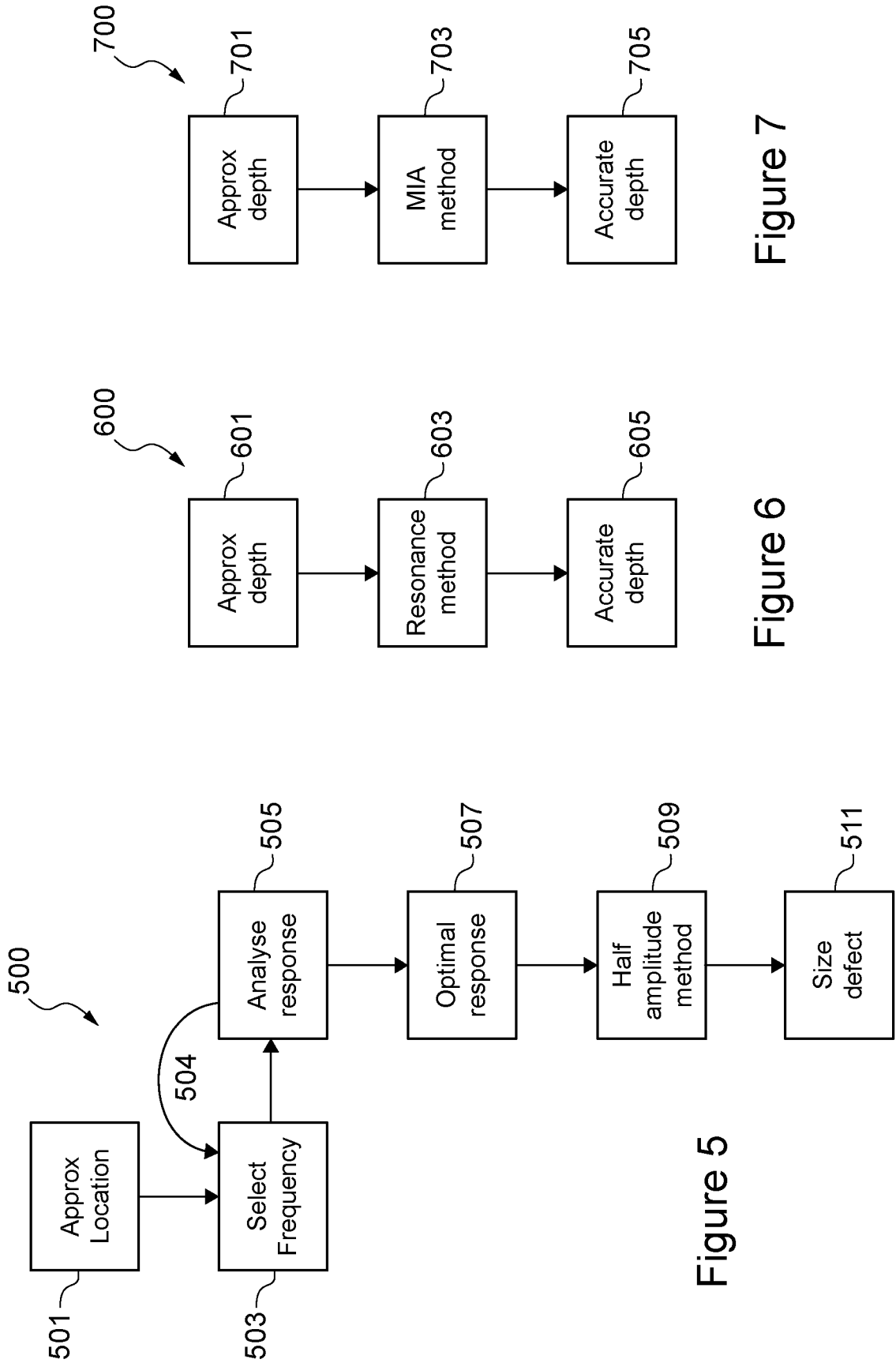


Figure 5

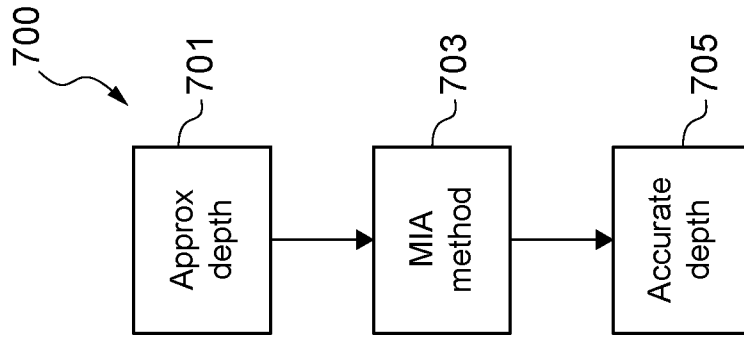


Figure 7

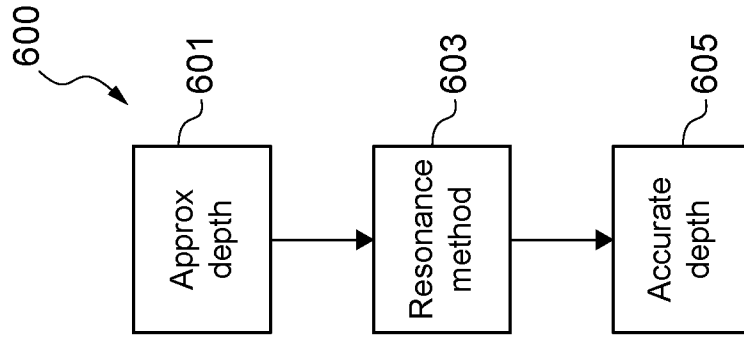


Figure 6

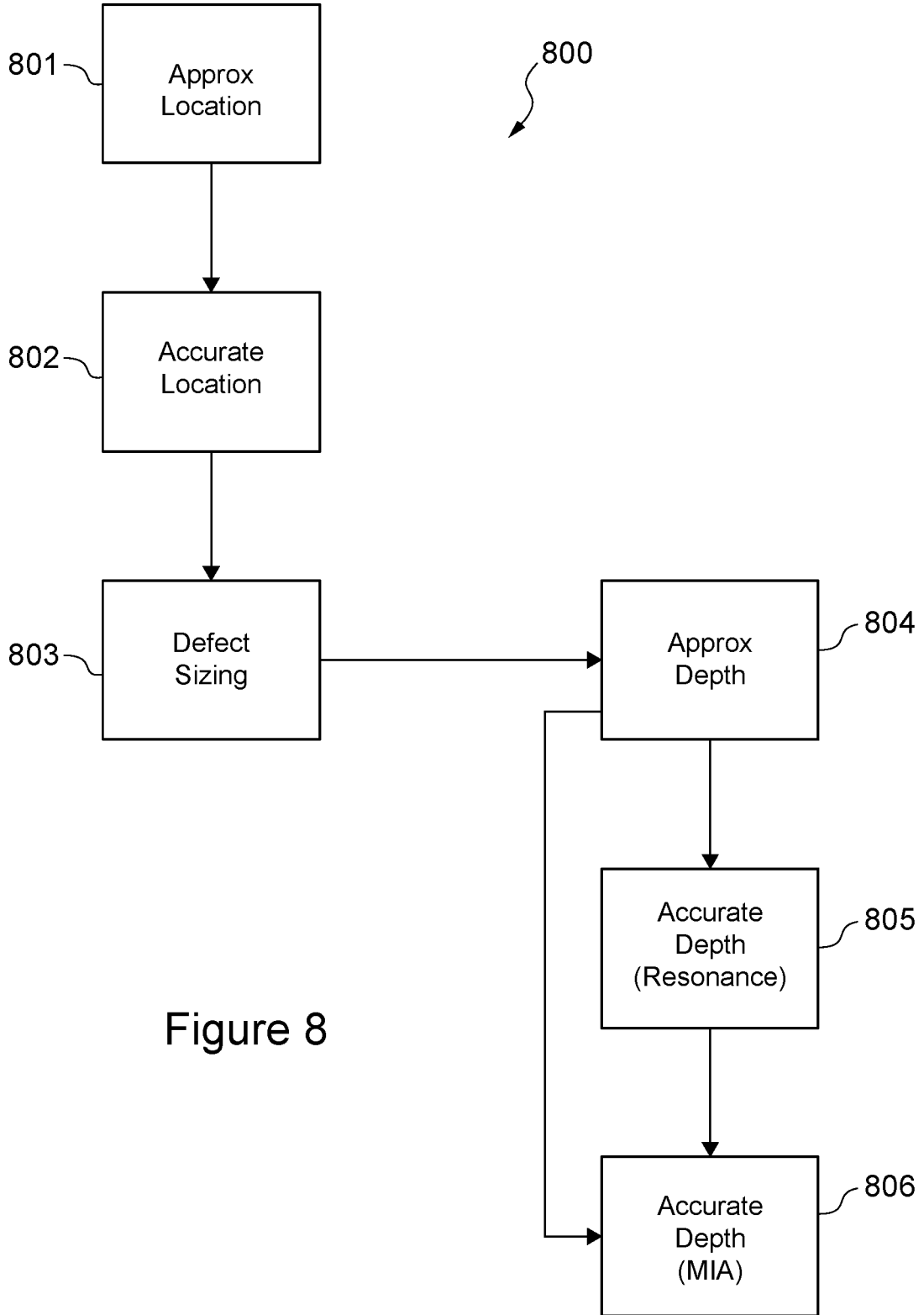


Figure 8