US 20250258139A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2025/0258139 A1**

KOBAYASHI et al. (43) **Pub. Date: Aug. 14, 2025**

(54) **ULTRASONIC DEFECT DETECTION APPARATUS AND ULTRASONIC DEFECT DETECTION METHOD**

(71) Applicant: **MITSUBISHI HEAVY INDUSTRIES, LTD.**, Tokyo (JP)

(72) Inventors: **Seiji KOBAYASHI**, Tokyo (JP); **Kyohei HAYASHI**, Tokyo (JP); **Mitsuyoshi UEMATSU**, Tokyo (JP)

(73) Assignee: **MITSUBISHI HEAVY INDUSTRIES, LTD.**, Tokyo (JP)

(21) Appl. No.: **18/857,651**

(22) PCT Filed: **Feb. 17, 2023**

(86) PCT No.: **PCT/JP2023/005729**

§ 371 (c)(1),
(2) Date: **Oct. 17, 2024**

(30) **Foreign Application Priority Data**

Apr. 28, 2022 (JP) 2022-074353

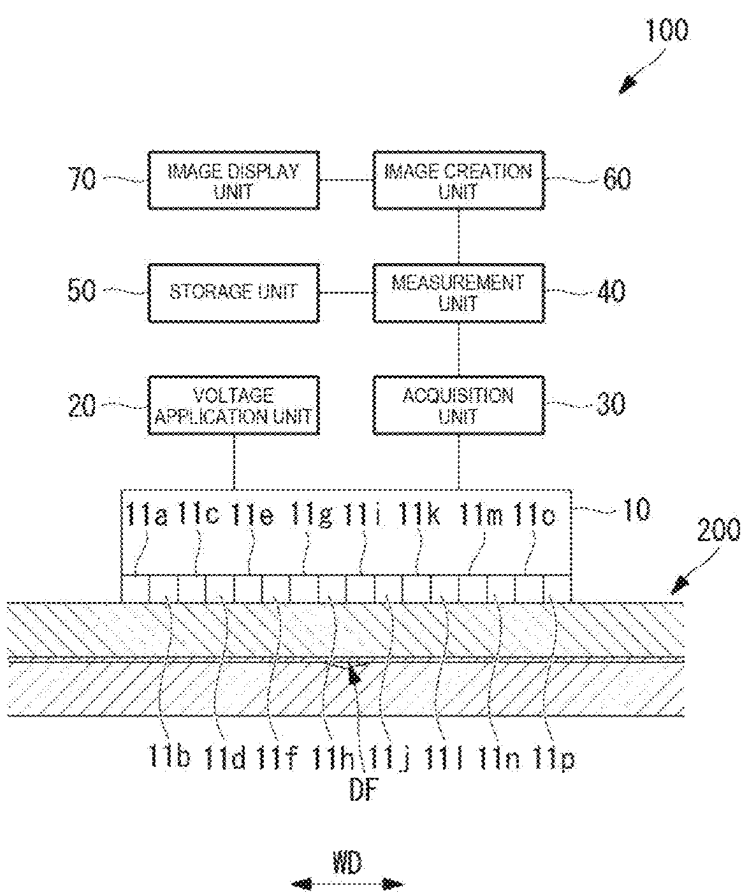
Publication Classification

(51) **Int. Cl.**
G01N 29/06 (2006.01)

(52) **U.S. Cl.**
CPC ... ***G01N 29/0645*** (2013.01); *G01N 2291/023* (2013.01); *G01N 2291/0289* (2013.01); *G01N 2291/106* (2013.01)

(57) **ABSTRACT**

Provided is an ultrasonic defect detection apparatus (**100**) including an ultrasonic array probe (**10**), a voltage application element (**20**) that executes a voltage application operation including a first operation of simultaneously applying a predetermined voltage to a predetermined number of ultrasonic elements and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings, an acquisition element (**30**) that acquires a differential response value, which is a difference between a first response value of ultrasonic waves of a predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of ultrasonic waves of a predetermined frequency received by the ultrasonic array probe at different timings in the second operation, and a measurement element (**40**) that measures an opening width of a defect (DF) based on the plurality of differential response values acquired by the acquisition element (**30**) when the voltage applying unit (**20**) executes the voltage application operation at a plurality of predetermined voltages having different voltage values.



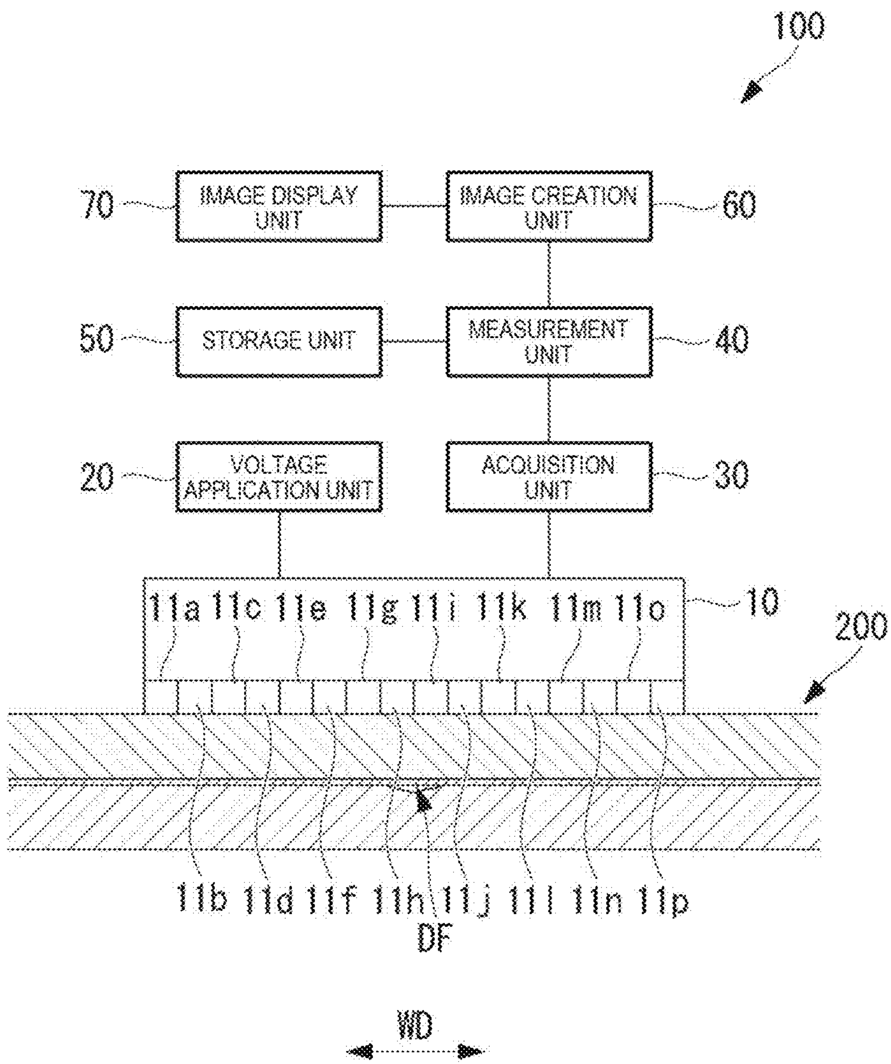

100
70
IMAGE DISPLAY UNIT
IMAGE CREATION UNIT
60
50
STORAGE UNIT
MEASUREMENT UNIT
40
20
VOLTAGE APPLICATION UNIT
ACQUISITION UNIT
30
11a 11c 11e 11g 11i 11k 11m 11o
10
200
11b 11d 11f 11h 11j 11l 11n 11p
DF
WD

FIG. 1

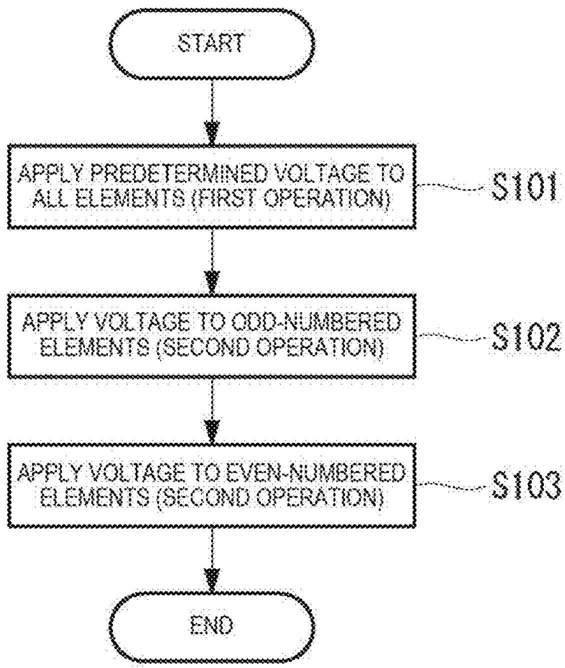

START
APPLY PREDETERMINED VOLTAGE TO ALL ELEMENTS (FIRST OPERATION)
S101
APPLY VOLTAGE TO ODD-NUMBERED ELEMENTS (SECOND OPERATION)
S102
APPLY VOLTAGE TO EVEN-NUMBERED ELEMENTS (SECOND OPERATION)
S103
END

FIG. 2

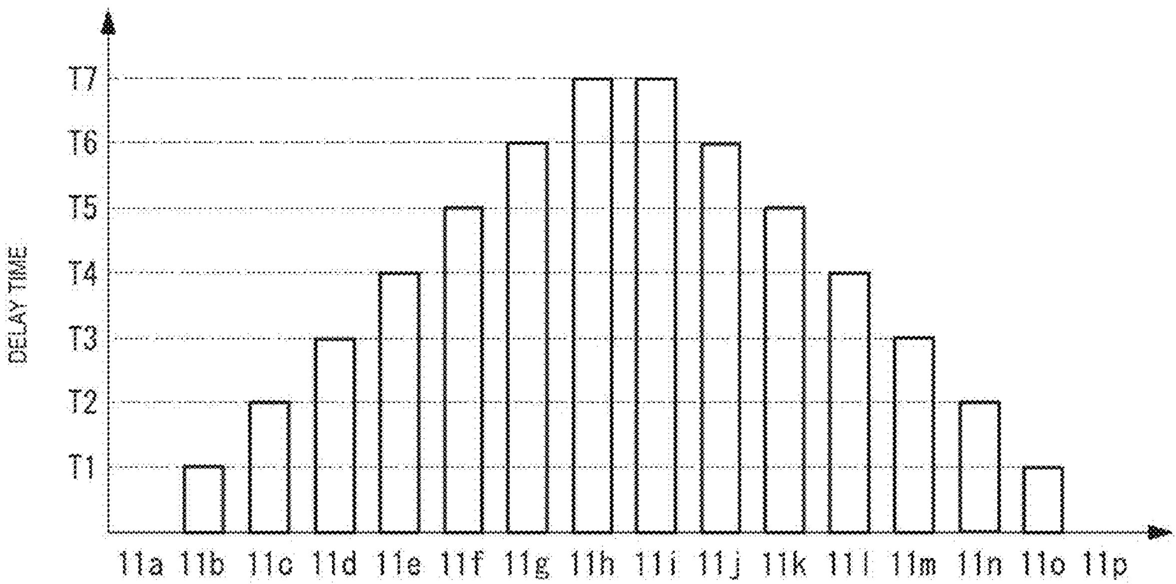
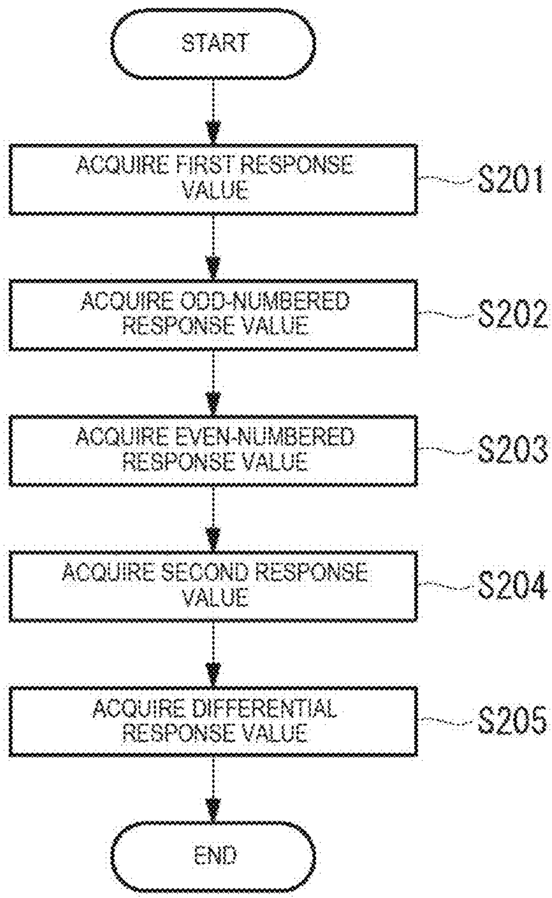

DELAY TIME
T7
T6
T5
T4
T3
T2
T1
11a 11b 11c 11d 11e 11f 11g 11h 11i 11j 11k 11l 11m 11n 11o 11p

FIG. 3



START
ACQUIRE FIRST RESPONSE VALUE
S201
ACQUIRE ODD-NUMBERED RESPONSE VALUE
S202
ACQUIRE EVEN-NUMBERED RESPONSE VALUE
S203
ACQUIRE SECOND RESPONSE VALUE
S204
ACQUIRE DIFFERENTIAL RESPONSE VALUE
S205
END

FIG. 4

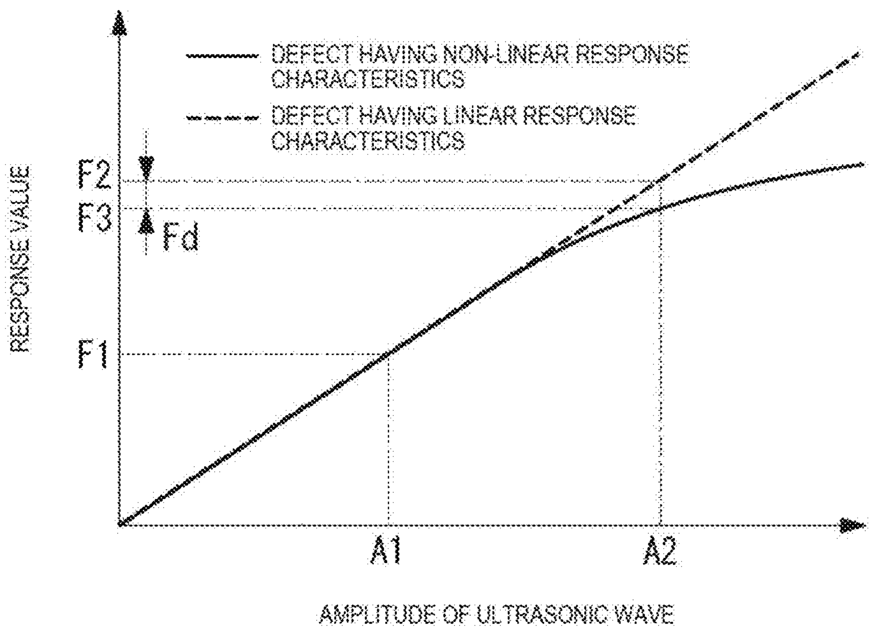

DEFECT HAVING NON-LINEAR RESPONSE CHARACTERISTICS
DEFECT HAVING LINEAR RESPONSE CHARACTERISTICS
RESPONSE VALUE
F2
F3
Fd
F1
A1
A2
AMPLITUDE OF ULTRASONIC WAVE

FIG. 5

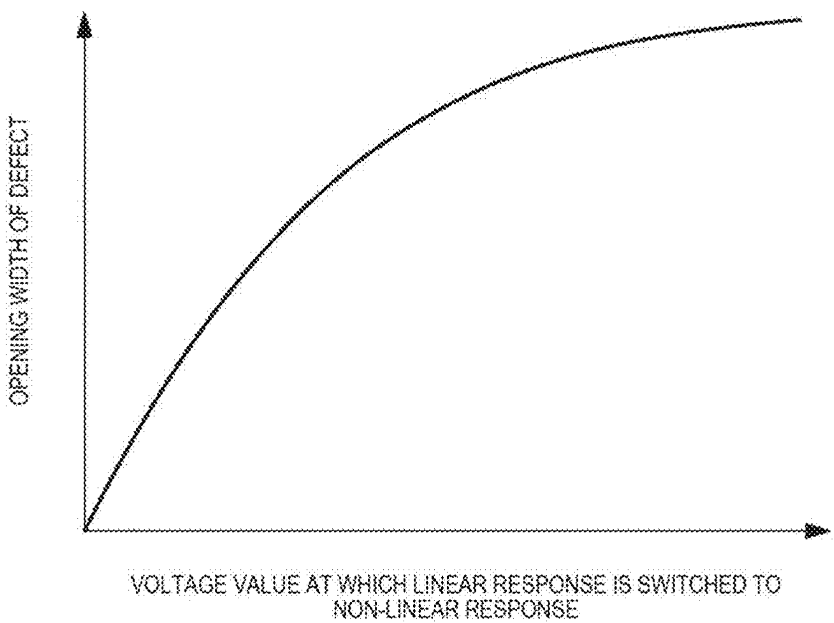

OPENING WIDTH OF DEFECT
VOLTAGE VALUE AT WHICH LINEAR RESPONSE IS SWITCHED TO NON-LINEAR RESPONSE

FIG. 6

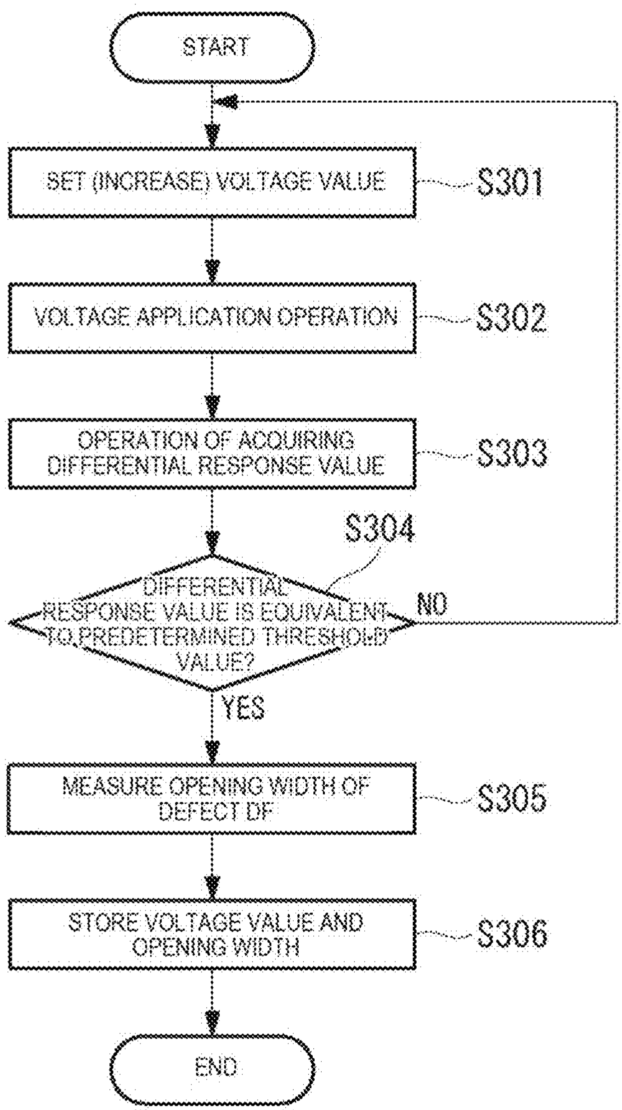

START
SET (INCREASE) VOLTAGE VALUE
S301
VOLTAGE APPLICATION OPERATION
S302
OPERATION OF ACQUIRING DIFFERENTIAL RESPONSE VALUE
S303
S304
DIFFERENTIAL RESPONSE VALUE IS EQUIVALENT TO PREDETERMINED THRESHOLD VALUE?
NO
YES
MEASURE OPENING WIDTH OF DEFECT DF
S305
STORE VOLTAGE VALUE AND OPENING WIDTH
S306
END

FIG. 7

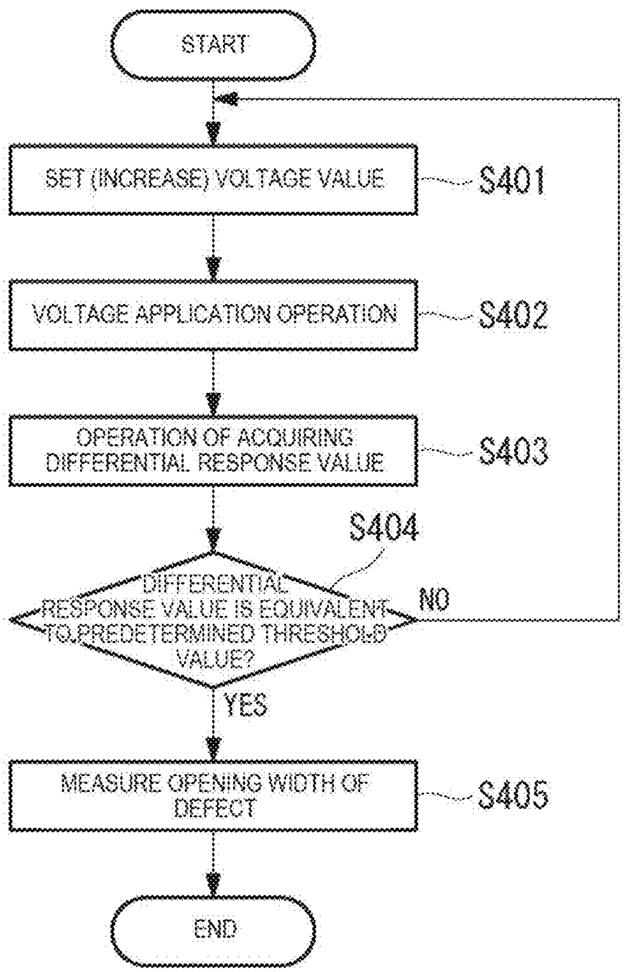

START
SET (INCREASE) VOLTAGE VALUE
S401
VOLTAGE APPLICATION OPERATION
S402
OPERATION OF ACQUIRING DIFFERENTIAL RESPONSE VALUE
S403
S404
DIFFERENTIAL RESPONSE VALUE IS EQUIVALENT TO PREDETERMINED THRESHOLD VALUE?
NO
YES
MEASURE OPENING WIDTH OF DEFECT
S405
END

FIG. 8

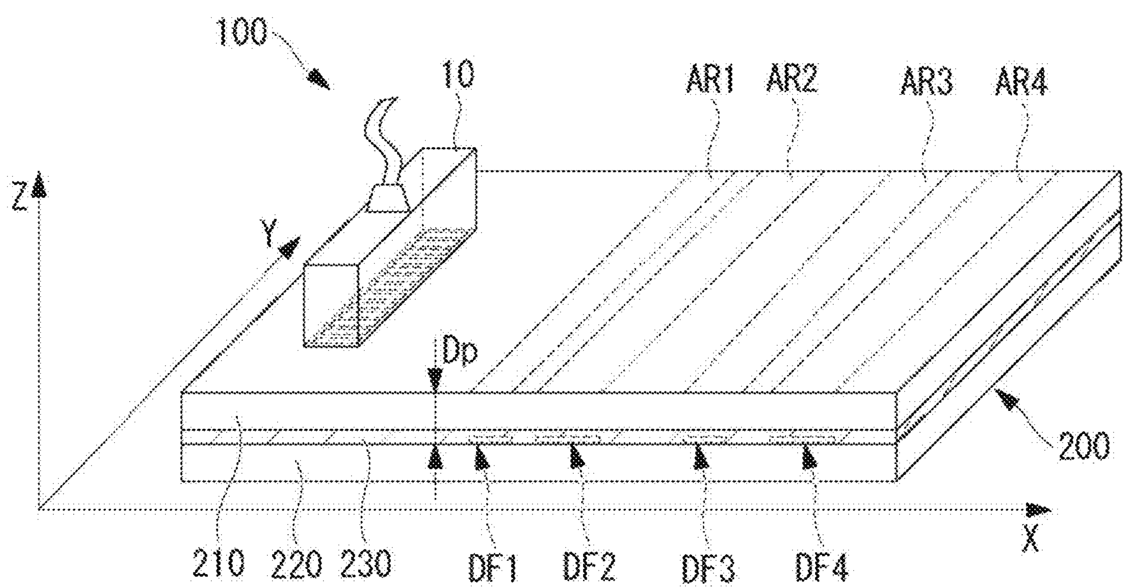


FIG. 9

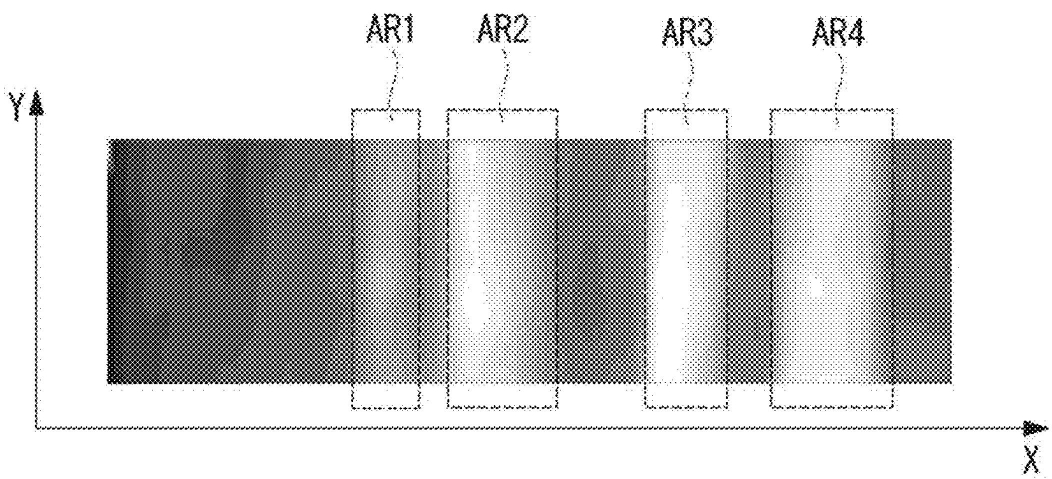


FIG. 10

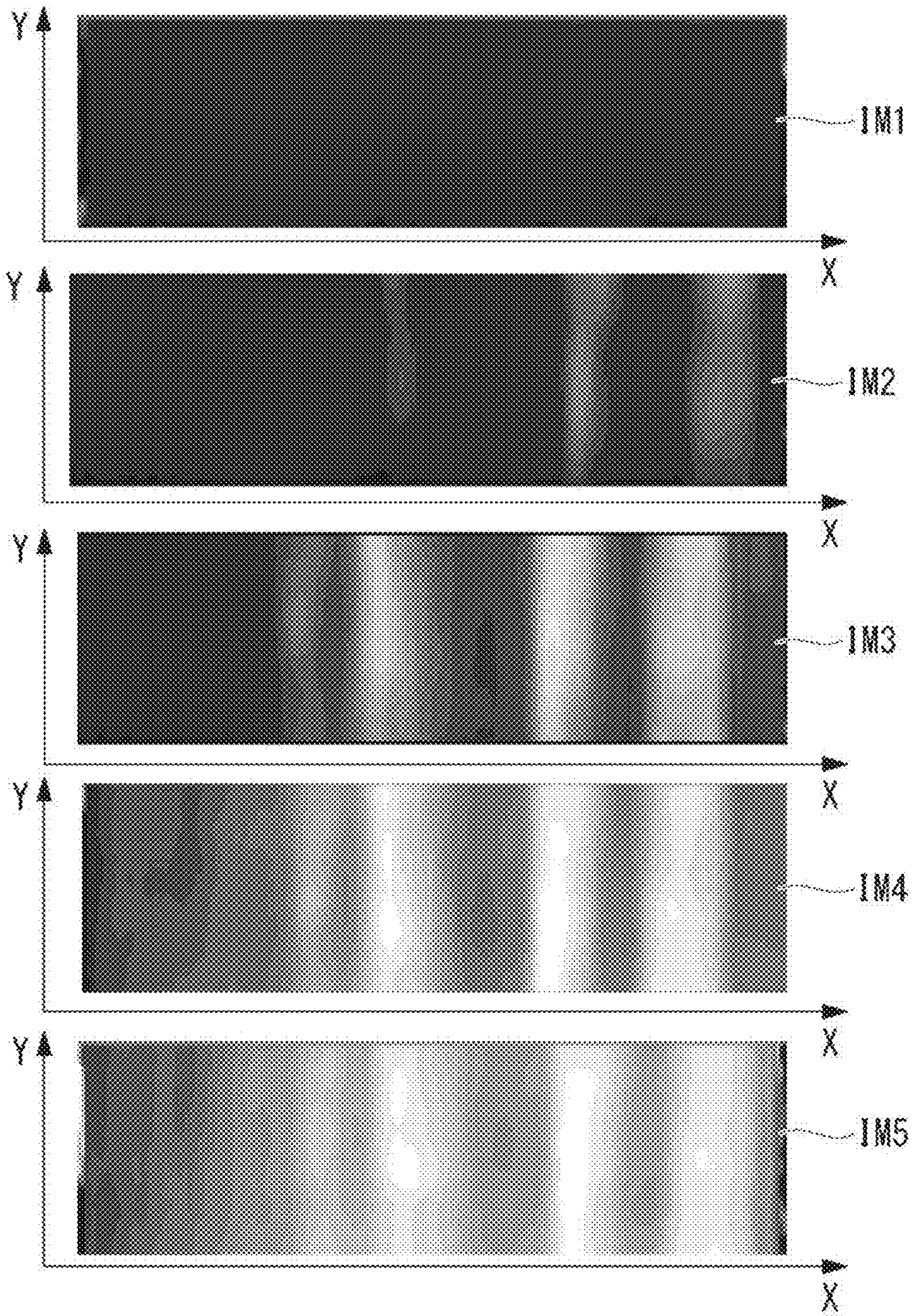


FIG. 11

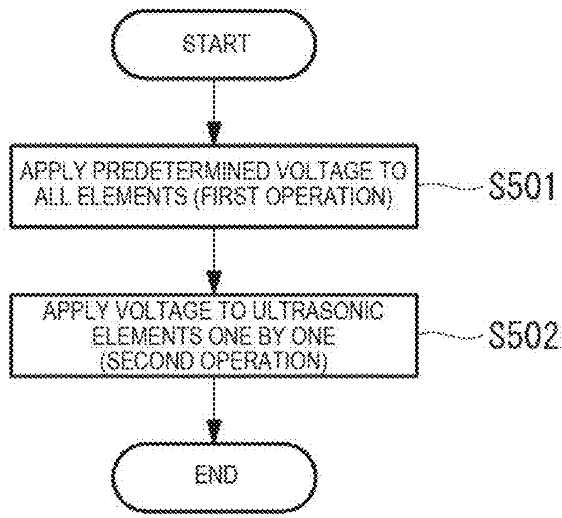

START
APPLY PREDETERMINED VOLTAGE TO ALL ELEMENTS (FIRST OPERATION)
S501
APPLY VOLTAGE TO ULTRASONIC ELEMENTS ONE BY ONE (SECOND OPERATION)
S502
END

FIG. 12

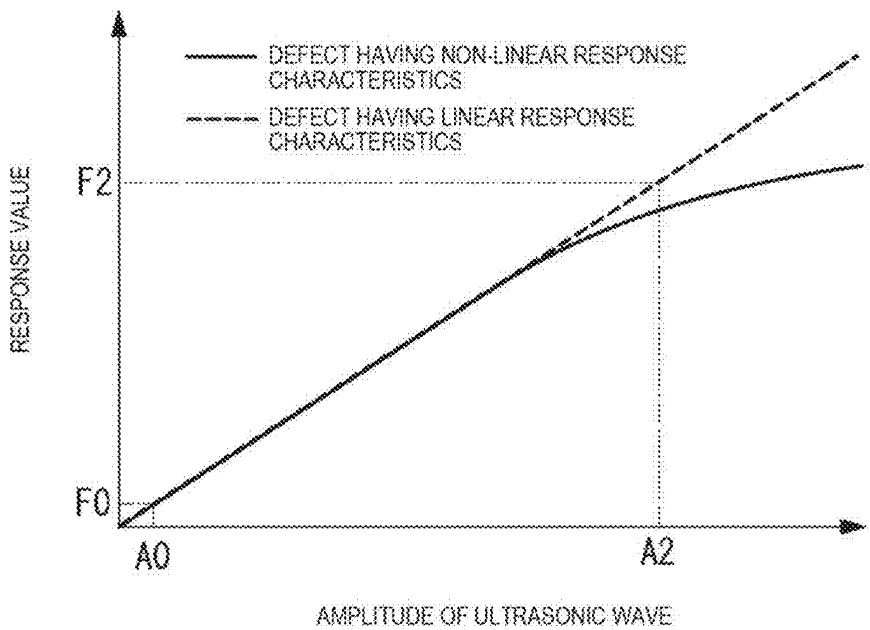

DEFECT HAVING NON-LINEAR RESPONSE CHARACTERISTICS
DEFECT HAVING LINEAR RESPONSE CHARACTERISTICS
RESPONSE VALUE
F2
F0
A0
A2
AMPLITUDE OF ULTRASONIC WAVE

FIG. 13

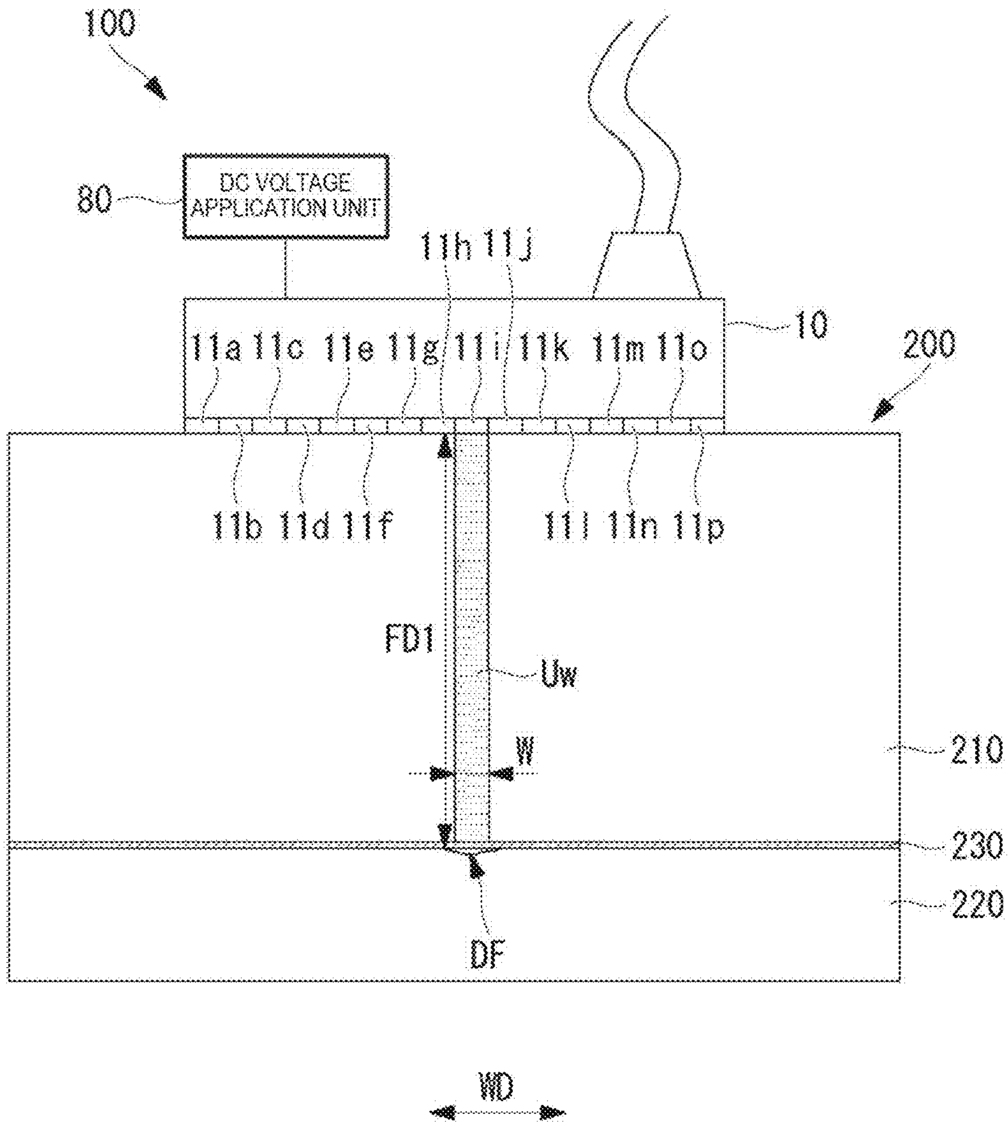

100
80
DC VOLTAGE APPLICATION UNIT
11h 11j
10
11a 11c 11e 11g 11i 11k 11m 11o
200
11b 11d 11f
11l 11n 11p
FD1
Uw
W
210
230
220
DF
WD

FIG. 14

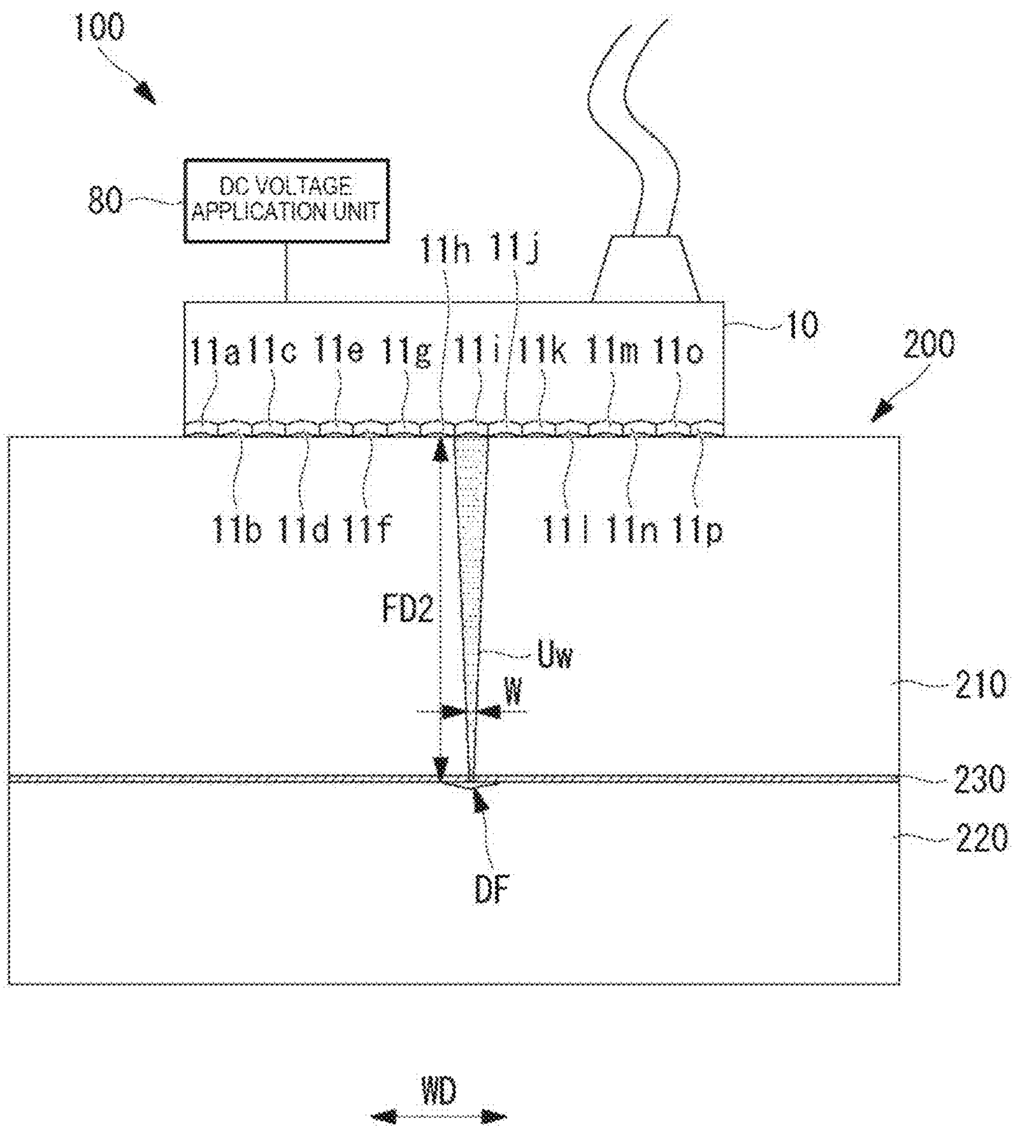

100
80
DC VOLTAGE
APPLICATION UNIT
11h 11j
10
11a 11c 11e 11g 11i 11k 11m 11o
200
11b 11d 11f
11l 11n 11p
FD2
Uw
W
210
230
220
DF
WD

FIG. 15

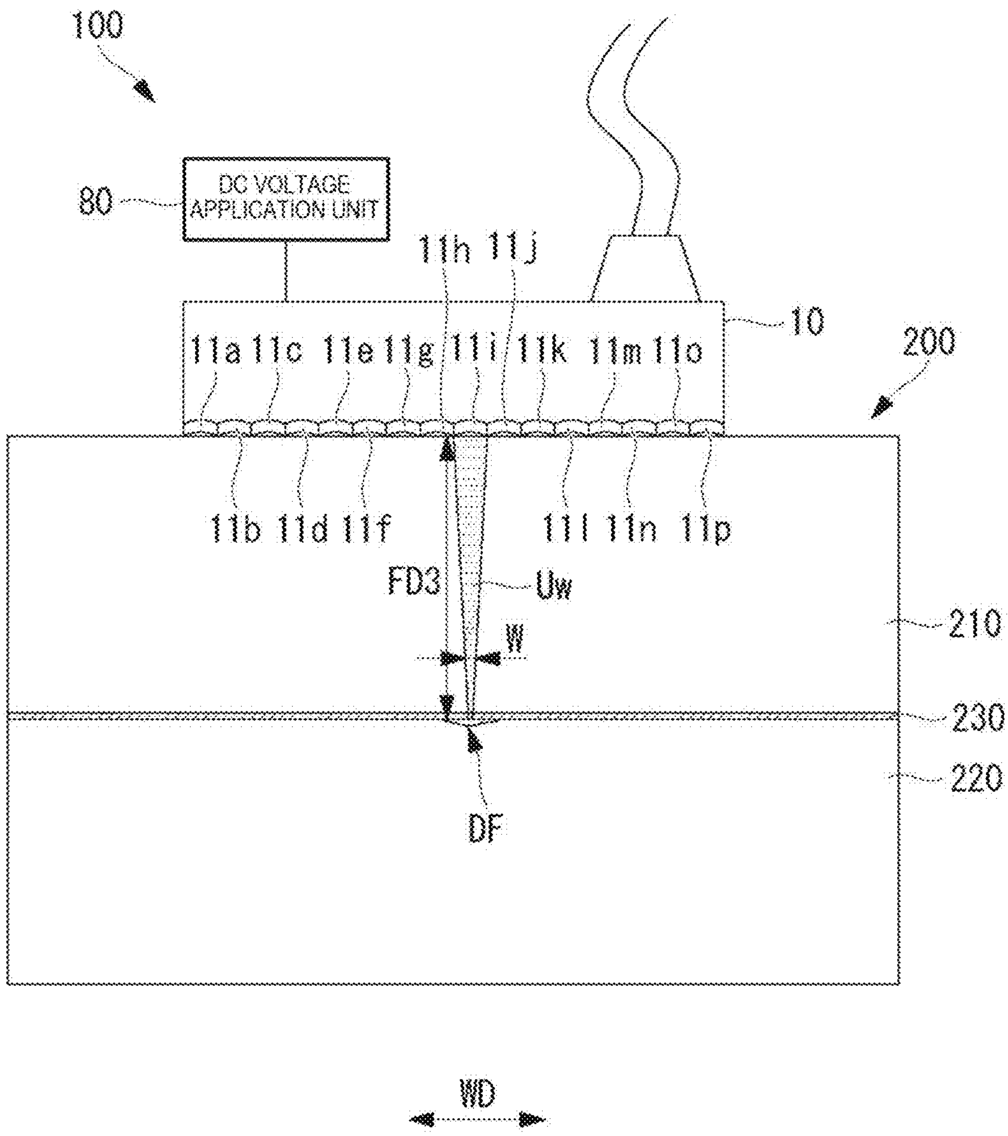

100
80
DC VOLTAGE APPLICATION UNIT
11h 11j
10
11a 11c 11e 11g 11i 11k 11m 11o
200
11b 11d 11f
11l 11n 11p
FD3
Uw
W
210
230
220
DF
WD

FIG. 16

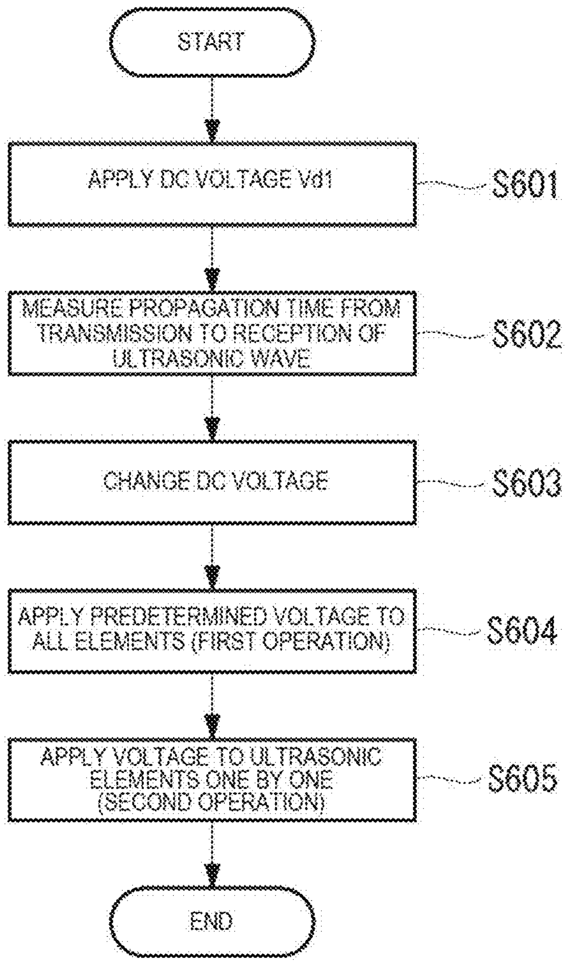

START
APPLY DC VOLTAGE Vd1
S601
MEASURE PROPAGATION TIME FROM TRANSMISSION TO RECEPTION OF ULTRASONIC WAVE
S602
CHANGE DC VOLTAGE
S603
APPLY PREDETERMINED VOLTAGE TO ALL ELEMENTS (FIRST OPERATION)
S604
APPLY VOLTAGE TO ULTRASONIC ELEMENTS ONE BY ONE (SECOND OPERATION)
S605
END

FIG. 17

ULTRASONIC DEFECT DETECTION APPARATUS AND ULTRASONIC DEFECT DETECTION METHOD

TECHNICAL FIELD

[0001] The present disclosure relates to an ultrasonic defect detection apparatus and an ultrasonic defect detection method.

BACKGROUND ART

[0002] In the related art, a technique of measuring a defect such as a closed crack or a crack having a minute opening width in an inspection object using ultrasonic waves is known (for example, see Patent Document 1). Patent Document 1 discloses a technique in which a plurality of types of ultrasonic waves having mutually different amplitudes at a predetermined fundamental frequency are transmitted to an inspection object as transmission signals, ultrasonic waves reflected from the inspection object are received, and a defect of the inspection object is visualized from a difference in response intensities with respect to the different amplitudes.

CITATION LIST

Patent Literature

[0003] Patent Document 1: JP 6025049 B

SUMMARY OF INVENTION

Technical Problem

[0004] In Patent Document 1, it is possible to detect whether there is a defect having non-linearity in which the reflection intensities of the received signals are not proportional to the magnitudes of the amplitudes of the transmitted signals by visualizing the difference between the response intensities with respect to the different amplitudes. However, Patent Document 1 visualizes the difference in the response intensities with respect to the different amplitudes, and does not measure the size of the defect (for example, the opening width of a crack) itself.

[0005] The present disclosure has been made in view of such circumstances, and an object thereof is to provide an ultrasonic defect detection apparatus and an ultrasonic defect detection method that can measure an opening width of a defect having non-linear response characteristics in which a response value of a received ultrasonic wave is not proportional to a magnitude of an amplitude of a transmitted ultrasonic wave.

Solution to Problem

[0006] In order to solve the above-described problem, the present disclosure employs the following means.

[0007] An ultrasonic defect detection apparatus according to one aspect of the present disclosure includes:

[0008] an ultrasonic array probe including a predetermined number of ultrasonic elements arranged along a predetermined direction, each of the ultrasonic elements transmitting an ultrasonic wave of a predetermined frequency to an inspection object and receiving the ultrasonic wave of the predetermined frequency reflected by the inspection object;

[0009] a voltage application element executing a voltage application operation, the voltage application operation including a first operation of simultaneously applying a predetermined voltage to the predetermined number of ultrasonic elements, and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings;

[0010] an acquisition element acquiring a differential response value, the differential response value being a difference between a first response value of the ultrasonic wave of the predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of the ultrasonic wave of the predetermined frequency received by the ultrasonic array probe at different timings in the second operation; and

[0011] a measurement element measuring an opening width of a defect in the inspection object based on a plurality of the differential response values acquired by the acquisition element when the voltage application element executes the voltage application operation at a plurality of the predetermined voltages having different voltage values.

[0012] An ultrasonic defect detection method according to one aspect of the present disclosure is an ultrasonic defect detection method for measuring an opening width of a defect in an inspection object with an ultrasonic defect detection apparatus, the ultrasonic defect detection apparatus including an ultrasonic array probe including a predetermined number of ultrasonic elements arranged along a predetermined direction, each of the ultrasonic elements transmitting an ultrasonic wave of a predetermined frequency to an inspection object and receiving the ultrasonic wave of the predetermined frequency reflected by the inspection object, the ultrasonic defect detection method including:

[0013] a voltage application process of executing a voltage application operation, the voltage application operation including a first operation of simultaneously applying a predetermined voltage to the predetermined number of ultrasonic elements, and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings;

[0014] an acquisition process of acquiring a differential response value, the differential response value being a difference between a first response value of the ultrasonic wave of the predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of the ultrasonic wave of the predetermined frequency received by the ultrasonic array probe at different timings in the second operation; and

[0015] a measurement process of measuring the opening width of the defect in the inspection object based on a plurality of the differential response values acquired in the acquisition process when the voltage application operation is executed at a plurality of the predetermined voltages having different voltage values in the voltage application process.

Advantageous Effects of Invention

[0016] According to the present disclosure, it is possible to provide an ultrasonic defect detection apparatus and an ultrasonic defect detection method that can measure an opening width of a defect having non-linear response characteristics in which a response value of a received ultrasonic wave is not proportional to a magnitude of an amplitude of a transmitted ultrasonic wave.

BRIEF DESCRIPTION OF DRAWINGS

[0017] FIG. **1** is a schematic configuration diagram of an ultrasonic defect detection apparatus according to a first embodiment of the present disclosure.

[0018] FIG. **2** is a flowchart illustrating a voltage application operation executed by a voltage application element.

[0019] FIG. **3** is a graph showing delay times of a voltage pulse applied to ultrasonic elements when the voltage application element executes a first operation.

[0020] FIG. **4** is a flowchart illustrating an operation of acquiring a differential response value executed by an acquisition element.

[0021] FIG. **5** is a graph showing a relationship between an amplitude of an ultrasonic wave and a response value acquired by the acquisition element.

[0022] FIG. **6** is a graph showing a relationship between a voltage value at which a linear response is transferred to a non-linear response and an opening width of a defect.

[0023] FIG. **7** is a flowchart illustrating an operation of creating a table to be stored in a storage element.

[0024] FIG. **8** is a flowchart illustrating an operation of measuring an opening width of a defect.

[0025] FIG. **9** is a perspective view illustrating a state in which an ultrasonic array probe is placed on a surface of an inspection object.

[0026] FIG. **10** is a diagram illustrating an example of a C-scan image displayed on an image display element.

[0027] FIG. **11** is a diagram illustrating an example of a C-scan image displayed on the image display element when the voltage application element switches a voltage value to be applied to the ultrasonic elements.

[0028] FIG. **12** is a flowchart illustrating a voltage application operation executed by the voltage application element.

[0029] FIG. **13** is a graph showing a relationship between an amplitude of an ultrasonic wave and a response value acquired by the acquisition element.

[0030] FIG. **14** is a front view illustrating a state in which a defect of the inspection object is scanned with an ultrasonic wave from a single ultrasonic element.

[0031] FIG. **15** is a front view illustrating a state in which a defect of the inspection object is scanned with an ultrasonic wave from a single ultrasonic element.

[0032] FIG. **16** is a front view illustrating a state in which a defect of the inspection object is scanned with an ultrasonic wave from a single ultrasonic element.

[0033] FIG. **17** is a flowchart illustrating a process in which a DC voltage applied from a DC voltage application element to the ultrasonic elements is changed so as to focus on an adhesive layer, and the voltage application element executes the voltage application operation.

DESCRIPTION OF EMBODIMENTS

First Embodiment

[0034] Hereinafter, an ultrasonic defect detection apparatus **100** according to a first embodiment of the present disclosure will be described with reference to the drawings. FIG. **1** is a schematic configuration diagram of the ultrasonic defect detection apparatus **100** according to the first embodiment of the present disclosure. The ultrasonic defect detection apparatus **100** of the present embodiment is an apparatus that measures an opening width of a defect DF in an inspection object **200**.

[0035] As illustrated in FIG. **1**, the ultrasonic defect detection apparatus **100** includes an ultrasonic array probe **10**, a voltage application element **20**, an acquisition element **30**, a measurement element **40**, a storage element **50**, an image creation element **60**, and an image display element **70**.

[0036] The ultrasonic array probe **10** includes a predetermined number of ultrasonic elements **11***a* to **11***p* that transmit an ultrasonic wave of a predetermined frequency to the inspection object **200** and receive the ultrasonic wave of the predetermined frequency reflected by the inspection object **200**. The predetermined number of ultrasonic elements **11***a* to **11***p* are arranged along a width direction (predetermined direction) WD.

[0037] FIG. **1** illustrates 16 ultrasonic elements arranged along the width direction WD, but an arbitrary number (e.g., 32, 64, or 128) of ultrasonic elements other than 16 may be arranged. The ultrasonic elements **11***a* to **11***p* receive the reflected wave of the transmitted ultrasonic wave of the predetermined frequency, output a response value corresponding to the intensity of the reflected wave, and transmit the response value to the acquisition element **30**.

[0038] The voltage application element **20** applies a voltage pulse having a predetermined waveform and a predetermined frequency to the ultrasonic elements **11***a* to **11***p* to transmitan ultrasonic wave. The voltage pulse applied to the ultrasonic elements **11***a* to **11***p* by the voltage application element **20** is, for example, a spike pulse or a rectangular pulse. The voltage application element **20** executes a voltage application operation including a first operation of simultaneously applying a predetermined voltage to all the ultrasonic elements **11***a* to **11***p* and a second operation of dividing the ultrasonic elements **11***a* to **11***p* into a plurality of element groups and applying a predetermined voltage to each element group at different timings.

[0039] FIG. **2** is a flowchart illustrating the voltage application operation executed by the voltage application element **20**.

[0040] In step S**101**, the voltage application element **20** executes the first operation of simultaneously applying a predetermined voltage to all the ultrasonic elements **11***a* to **11***p*. Here, "simultaneously applying" means continuously performing an operation of applying a voltage pulse to all the ultrasonic elements **11***a* to **11***p* while delaying the voltage pulse applied to the ultrasonic elements **11***a* to **11***p* by delay times.

[0041] In the present embodiment, the voltage application element **20** executes the voltage application operation using a phased array excitation method so as to provide a focal point at the central portion of the ultrasonic array probe **10** in the width direction WD. FIG. **3** is a graph showing delay times of the voltage pulse applied to the ultrasonic elements **11**a to **11**p when the voltage application element **20** executes the first operation.

[0042] As shown in FIG. **3**, the delay time of the voltage pulse applied to the ultrasonic elements **11**a and **11**p arranged at both ends in the width direction WD is zero. The delay time of the voltage pulse applied to the ultrasonic elements **11**b and **11**o is T**1**. The delay time of the voltage pulse applied to the ultrasonic elements **11**c and **11**n is T**2**. The delay time of the voltage pulse applied to the ultrasonic elements **11**d and **11**m is T**3**. The delay time of the voltage pulse applied to the ultrasonic elements **11**e and **11**l is T**4**. The delay time of the voltage pulse applied to the ultrasonic elements **11**f and **11**k is T**5**. The delay time of the voltage pulse applied to the ultrasonic elements **11**g and **11**j is T**6**. The delay time of the voltage pulse applied to the ultrasonic elements **11**h and **11**i is T**7**.

[0043] As shown in FIG. **3**, with respect to the voltage pulse applied to the ultrasonic elements **11**a and **11**p arranged at both ends in the width direction WD, the shorter the distance to the central portion in the width direction WD, the longer the delay time of the voltage pulse applied to the ultrasonic elements.

[0044] In the first operation in step S**101**, the reflected waves of the ultrasonic waves transmitted by all the ultrasonic elements **11**a to **11**p are received by the ultrasonic elements **11**a to **11**p. The ultrasonic array probe **10** calculates a response value by performing a binning process of integrating **16** output values obtained by the ultrasonic elements **11**a to **11**p receiving the reflected waves, and outputs the response value to the acquisition element **30**.

[0045] In step S**102** and step S**103**, the voltage application element **20** executes the second operation of dividing the ultrasonic elements **11**a to **11**p into a plurality of element groups and applying a predetermined voltage to each of the element groups at different timings.

[0046] In step S**102**, the voltage application element **20** simultaneously applies the predetermined voltage to a first element group including 8 odd-numbered ultrasonic elements **11**a, **11**c, **11**e, **11**g, **11**i, **11**k, **11**m, and **11**o from one end in the width direction WD among the plurality of ultrasonic elements **11**a to **11**p. Here, "simultaneously applies" means continuously performing an operation of applying a voltage pulse to the odd-numbered ultrasonic elements **11**a, **11**c, **11**e, **11**g, **11**i, **11**k, **11**m, and **11**o while delaying the voltage pulse applied to the odd-numbered ultrasonic elements **11**a, **11**c, **11**e, **11**g, **11**i, **11**k, **11**m, and **110** by the delay times. In step S**102**, the voltage application element **20** does not apply the predetermined voltage to the even-numbered ultrasonic elements **11**b, **11**d, **11**f, **11**h, **11**j, **11**l, **11**n, and **11**p.

[0047] In step S**103**, the voltage application element **20** simultaneously applies the predetermined voltage to a second element group including 8 even-numbered ultrasonic elements **11**b, **11**d, **11**f, **11**h, **11**j, **11**l, **11**n, and **11**p from one end in the width direction WD among the plurality of ultrasonic elements **11**a to **11**p. Here, "simultaneously applies" means continuously performing an operation of applying a voltage pulse to the even-numbered ultrasonic elements **11**b, **11**d, **11**f, **11**h, **11**j, **11**l, **11**n, and **11**p while delaying the voltage pulse applied to the even-numbered ultrasonic elements **11**b, **11**d, **11**f, **11**h, **11**j, **11**l, **11**n, and **11**p by the delay times. In step S**103**, the voltage application element **20** does not apply the predetermined voltage to the odd-numbered ultrasonic elements **11**a, **11**c, **11**e, **11**g, **11**i, **11**k, **11**m, and **11**o.

[0048] In the second operation including step S**102** and step S**103**, the reflected waves of the ultrasonic waves transmitted by the odd-numbered ultrasonic elements **11**a, **11**c, **11**e, **11**g, **11**i, **11**k, **11**m, and **11**o are received by the ultrasonic elements **11**a to **11**p. A response value is calculated by performing a binning process of integrating **16** output values obtained by the ultrasonic elements **11**a to **11**p receiving the reflected waves, and the response value is output to the acquisition element **30**.

[0049] In addition, in the second operation, the reflected waves of the ultrasonic waves transmitted by the even-numbered ultrasonic elements **11**b, **11**d, **11**f, **11**h, **11**j, **11**l, **11**n, and **11**p are received by the ultrasonic elements **11**a to **11**p. A response value is calculated by performing a binning process of integrating **16** output values obtained by the ultrasonic elements **11**a to **11**p receiving the reflected waves, and the response value is output to the acquisition element **30**.

[0050] The acquisition element **30** acquires a first response value of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe **10** in the first operation of the voltage application element **20** and a second response value obtained by adding a plurality of response values of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe **10** at different timings in the second operation of the voltage application element **20**, and acquires a differential response value which is a difference between the first response value and the second response value.

[0051] FIG. **4** is a flowchart illustrating an operation of acquiring a differential response value executed by the acquisition element **30**.

[0052] In step S**201**, when the voltage application element **20** executes the first operation, the acquisition element **30** acquires a response value (first response value) output from the ultrasonic array probe **10** with respect to the reflected waves of the ultrasonic waves transmitted by the ultrasonic elements **11**a to **11**p.

[0053] In step S**202**, when the voltage application element **20** executes the second operation, the acquisition element **30** acquires an odd-numbered response value corresponding the odd-numbered ultrasonic elements output from the ultrasonic array probe **10** with respect to the reflected waves of the ultrasonic waves transmitted by the odd-numbered ultrasonic elements **11**a, **11**c, **11**e, **11**g, **11**i, **11**k, **11**m, and **11**o.

[0054] In step S**203**, when the voltage application element **20** executes the second operation, the acquisition element **30** acquires an even-numbered response value corresponding to the even-numbered ultrasonic elements output from the ultrasonic array probe **10** with respect to the reflected waves of the ultrasonic waves transmitted by the even-numbered ultrasonic elements **11**b, **11**d, **11**f, **11**h, **11**j, **11**l, **11**n, and **11**p.

[0055] In step S**204**, the acquisition element **30** adds the odd-numbered response value corresponding to the odd-numbered ultrasonic elements and the even-numbered response value corresponding to the even-numbered ultrasonic elements to obtain an added response value (second response value).

[0056] In step S**205**, the acquisition element **30** acquires a differential response value which is a difference between the first response value and the second response value.

[0057] As described above, the acquisition element **30** acquires the differential response value which is a difference between the first response value of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe **10** in the first operation of the voltage application element **20** and the second response value obtained by adding a plurality of response values (the odd-numbered response value corresponding to the odd-numbered ultrasonic elements and the even-numbered response value corresponding to the even-numbered ultrasonic elements) of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe **10** at different timings in the second operation of the voltage application element **20**.

[0058] The measurement element **40** measures an opening width of a defect DF in the inspection object **200** based on a plurality of the differential response values acquired by the acquisition element **30** when the voltage application element **20** executes the voltage application operation at a plurality of the predetermined voltages having different voltage values.

[0059] Here, the relationship between an amplitude of an ultrasonic wave and a response value acquired by the acquisition element **30** will be described with reference to FIG. **5**. FIG. **5** is a graph showing the relationship between an amplitude of an ultrasonic wave and a response value acquired by the acquisition element **30**. In FIG. **5**, a solid line indicates a defect in which the opening width of the defect DF of the inspection object **200** is minute and which exhibits non-linear response characteristics. A dotted line indicates a defect in which the opening width of the defect DF of the inspection object **200** is large and which exhibits linear response characteristics.

[0060] In FIG. **5**, an amplitude A**2** indicates an example of the amplitude of the ultrasonic waves output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the first operation. An amplitude A**1** indicates an example of the amplitude of the ultrasonic waves output from the odd-numbered ultrasonic elements **11***a*, **11***c*, **11***e*, **11***g*, **11***i*, **11***k*, **11***m*, and **11***o* or the even-numbered ultrasonic elements **11***b*, **11***d*, **11***f*, **11***h*, **11***j*, **11***l*, **11***n*, and **11***p* when the voltage application element **20** executes the second operation.

[0061] In the case where the defect DF has linear response characteristics in which the magnitude of the response value of the reflected ultrasonic waves is proportional to the magnitude of the amplitude of the ultrasonic waves transmitted from the ultrasonic elements **11***a* to **11***p*, since the second operation uses half of the number of the ultrasonic elements used in the first operation, the amplitude A**1** is substantially half the amplitude A**2**. The response value acquired by the acquisition element **30** with respect to the ultrasonic waves having the amplitude A**1** is F**1**, and the response value acquired by the acquisition element **30** with respect to the ultrasonic waves having the amplitude A**2** is F**2**. Since the response value F**1** is substantially half the response value F**2**, the differential response value is zero or a minute value.

[0062] This is because, in the case of the defect DF having linear response characteristics, the first response value (F**2**) obtained by adding response values output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the first operation is substantially the same as the second response value (F**1**×2) obtained by adding response values output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the second operation.

[0063] On the other hand, in the case where the defect DF having non-linear response characteristics in which the magnitude of the response value of the reflected ultrasonic waves is not proportional to the magnitude of the amplitude of the ultrasonic waves transmitted from the ultrasonic elements **11***a* to **11***p*, the response value acquired by the acquisition element **30** with respect to the ultrasonic waves having the amplitude A**2** is F**3** which is smaller than F**2**. The value obtained by subtracting F**3** from F**2** is a differential response value Fd. As shown in FIG. **5**, the differential response value Fd increases as the magnitude of the amplitude increases.

[0064] This is because, in the case of the defect DF having non-linear response characteristics, the first response value (F**3**) obtained by adding response values output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the first operation is smaller than the second response value (F**1**×2=F**2**) obtained by adding response values output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the second operation.

[0065] The reason why the first response value is smaller than the second response value in the case of the defect DF having non-linear response characteristics is that the energy of the ultrasonic waves output from all of the ultrasonic elements **11***a* to **11***p* with respect to the defect DF of the inspection object **200** is large, and a part of the opening (crack surface) of the defect DF is closed to come into contact, and whereby part of the ultrasonic waves is not reflected.

[0066] The defect DF having non-linear response characteristics exhibits linear response characteristics when the amplitude is small, but exhibits non-linear response characteristics when the amplitude increases. In addition, the larger the opening width of the defect DF is, the larger the amplitude (a voltage applied by the voltage application element **20**) at the time of transferring from a state indicating linear response characteristics to a state indicating non-linear response characteristics is.

[0067] Thus, the ultrasonic defect detection apparatus **100** of the present embodiment acquires a plurality of the differential response values acquired by the acquisition element **30** when the voltage application element **20** executes the voltage application operation at a plurality of the predetermined voltages having different voltage values, and refers to the voltage value of the predetermined voltage applied by the voltage application element **20** when the differential response value becomes a predetermined threshold value, thereby measuring the opening width of the defect DF in the inspection object **200**.

[0068] Specifically, the table shown in FIG. **6** is acquired using a test piece having the same structure and material as those of the inspection object **200** and stored in the storage element **50** in advance. Then, the measurement element **40** refers to the table to obtain the opening width of the defect DF from the voltage value of the predetermined voltage applied by the voltage application element **20** when the differential response value acquired by the acquisition element **30** becomes the predetermined threshold value.

[0069] Next, an operation of creating a table to be stored in the storage element **50** will be described with reference to

FIG. **7**. FIG. **7** is a flowchart illustrating the operation of creating a table to be stored in the storage element **50**.

[0070] When the flowchart illustrated in FIG. **7** is executed, the storage element **50** stores a table associating a voltage value of a predetermined voltage applied by the voltage application element **20** when a differential response value acquired by the acquisition element **30** becomes a predetermined threshold value and an opening width of the defect DF in the inspection object **200**.

[0071] In step S**301**, the voltage application element **20** sets a voltage value of a predetermined voltage to be applied to the ultrasonic elements **11***a* to **11***p*. When this setting is executed immediately after the start of this flowchart, the voltage application element **20** sets a voltage value at which the defect DF reliably exhibits linear response characteristics as the voltage value of the predetermined voltage. This is to search for a voltage value at which a state indicating linear response characteristics is transferred to a state indicating non-linear response characteristics by gradually increasing the voltage value of the predetermined voltage.

[0072] In step S**302**, the voltage application element **20** executes the voltage application operation illustrated in FIG. **2** at the voltage value of the predetermined voltage set in step S**301**.

[0073] In step S**303**, the acquisition element **30** executes the operation of acquiring a differential response value illustrated in FIG. **4**.

[0074] In step S**304**, the acquisition element **30** determines whether the differential response value acquired in step S**303** is a predetermined threshold value. If YES, the processing proceeds to step S**305**, and if NO, the processing from step S**301** is executed again. Note that, in step S**304**, when the differential response value exceeds the predetermined threshold value, it may be determined that the differential response value acquired in step S**303** is the predetermined threshold value.

[0075] When step S**301** is executed again, the voltage application element **20** increases the voltage value of the predetermined voltage. This is because the differential response value acquired in step S**303** is not the predetermined threshold value and the defect DF is in a state of exhibiting linear response characteristics, and thus a voltage value at which the defect DF is transferred to a state of exhibiting non-linear response characteristics is searched for.

[0076] When the differential response value acquired in step S**303** is the predetermined threshold value, it is understood that the present voltage value of the predetermined voltage is a voltage value at which the state indicating linear response characteristics is transferred to the state indicating non-linear response characteristics. Thus, in step S**305**, the opening width of the defect DF is measured with a laser displacement meter (not illustrated) or the like.

[0077] In step S**306**, the voltage value of the predetermined voltage applied by the voltage application element **20** when YES is determined in step S**304** and the opening width of the defect DF measured in step S**305** are associated with each other and stored in the storage element **50** as data of the table, and the flowchart is ended.

[0078] The processing of this flowchart is executed for each of a plurality of test pieces having different opening widths of defects, and a plurality of sets of data in which a voltage value of a predetermined voltage and a measurement value of an opening width of a defect are associated with each other is stored in the storage element **50**. In addition, in order to enable the measurement element **40** to measure (estimate) the opening width of the defect DF which has not been measured with a test piece, the table stored in the storage element **50** may be complemented as a function indicated by a straight line in FIG. **5** for a region in which there is no data associating a voltage value and an opening width of the defect DF with each other.

[0079] The defect DF that can be measured with a laser displacement meter (not illustrated) or the like needs to be exposed at a surface of a test piece. Thus, the test piece having a surface at which the defect DF is exposed is used. However, the defect DF actually measured by the ultrasonic defect detection apparatus **100** may not be exposed at a surface of the inspection object **200**.

[0080] Thus, when the defect DF that is not exposed at a surface of the inspection object **200** is actually measured by the ultrasonic defect detection apparatus **100**, the table obtained through the processing of this flowchart is corrected by using an analysis model of the defect DF that is not exposed at a surface of the inspection object **200**, and stored in the storage element **50**.

[0081] Next, an operation of measuring the opening width of the defect DF will be described with reference to FIG. **8**. FIG. **8** is a flowchart illustrating the operation of measuring the opening width of the defect DF.

[0082] In step S**401**, the voltage application element **20** sets a voltage value of a predetermined voltage to be applied to the ultrasonic elements **11***a* to **11***p*. When this setting is executed immediately after the start of this flowchart, the voltage application element **20** sets a voltage value at which the defect DF reliably exhibits linear response characteristics as the voltage value of the predetermined voltage. This is to search for a voltage value at which a state indicating linear response characteristics is transferred to a state indicating non-linear response characteristics by gradually increasing the voltage value of the predetermined voltage.

[0083] In step S**402**, the voltage application element **20** executes the voltage application operation illustrated in FIG. **2** at the voltage value of the predetermined voltage set in step S**401**.

[0084] In step S**403**, the acquisition element **30** executes the operation of acquiring a differential response value illustrated in FIG. **4**.

[0085] In step S**404**, the acquisition element **30** determines whether the differential response value acquired in step S**403** is a predetermined threshold value. If YES, the processing proceeds to step S**405**, and if NO, the processing from step S**401** is executed again. Note that, in step S**404**, when the differential response value exceeds the predetermined threshold value, it may be determined that the differential response value acquired in step S**403** is the predetermined threshold value.

[0086] When step S**401** is executed again, the voltage application element **20** increases the voltage value of the predetermined voltage. This is because the differential response value acquired in step S**403** is not the predetermined threshold value and the defect DF is in a state of exhibiting linear response characteristics, and thus a voltage value at which the defect DF is transferred to a state of exhibiting non-linear response characteristics is searched for. In this way, the voltage application element **20** executes the voltage application operation a plurality of times by switching the voltage value of the predetermined voltage such that the differential response value acquired by the acquisition element **30** becomes the predetermined threshold value.

[0087] When the differential response value acquired in step S**403** is the predetermined threshold value, it is understood that the present voltage value of the predetermined voltage is a voltage value at which the state indicating linear response characteristics is transferred to the state indicating non-linear response characteristics.

[0088] In step S**405**, the measurement element **40** measures the opening width based on the voltage value of the predetermined voltage applied by the voltage application element **20** when the differential response value acquired by the acquisition element **30** becomes the predetermined threshold value and the table stored in the storage element **50**. The measurement element **40** outputs the opening width corresponding to the voltage value by referring to the table stored in the storage element **50**. For example, the measurement element **40** displays the measured opening width at the image display element **70**. Through steps S**401** to S**405** described above, the opening width of the defect DF present at the location of the focal point can be measured at the position where the ultrasonic array probe **10** is currently arranged. Further, by moving the ultrasonic array probe **10** to an arbitrary position on a surface of the inspection object **200**, the opening width of the defect DF at the arbitrary position on the surface of the inspection object **200** can be measured.

[0089] FIG. **9** is a perspective view illustrating a state in which the ultrasonic array probe **10** of the present embodiment is installed at a surface of the inspection object **200**. The inspection object **200** illustrated in FIG. **9** is made by joining a pair of plate-like members **210** and **220** formed of carbon fiber reinforced plastic (CFRP) with an adhesive **230**.

[0090] In the inspection object **200**, the adhesive **230** is disposed at a position Dp in the Z-axis direction (depth direction) from a surface of the plate-like member **210**. The defect DF may occur in the position in the Z-axis direction where the adhesive **230** is disposed. Thus, for the ultrasonic array probe **10**, the focal point of the ultrasonic waves is set at the position Dp in the Z-axis direction from the surface of the plate-like member **210**.

[0091] In FIG. **9**, the direction in which the ultrasonic elements **11***a* to **11***p* are arranged in the ultrasonic array probe **10** is a direction along the Y axis. The ultrasonic defect detection apparatus **100** moves the ultrasonic array probe **10** along the X axis orthogonal to the Y axis so that the acquisition element **30** acquires a differential response value at each position on the X axis of the inspection object **200** and the measurement element **40** measures the opening width of the defect DF. Note that the ultrasonic defect detection apparatus **100** may move the ultrasonic array probe **10** along the Y axis so that the acquisition element **30** acquires a differential response value at each position on the Y axis of the inspection object **200** and the measurement element **40** measures the opening width of the defect DF.

[0092] The ultrasonic defect detection apparatus **100** can acquire a differential response value at each position on the Y axis of the inspection object **200** and measure the opening width in an area of the inspection object **200** which is in contact with the ultrasonic array probe **10**, without moving the ultrasonic array probe **10** along the Y axis.

[0093] Specifically, it is possible to acquire differential response values by using a selected part of the ultrasonic elements **11***a* to **11***p* (e.g., 8 sequentially-arranged ultrasonic elements out of 16 ultrasonic elements) and measure the opening width. By moving the combination of the selected part of the ultrasonic elements along the Y axis, it is possible to acquire a differential response value at each position on the Y axis of the inspection object **200** and measure the opening width in the area of the inspection object **200** which is in contact with the ultrasonic array probe **10**.

[0094] The image creation element **60** creates a C-scan image, which is a two-dimensional image, from differential intensities acquired by the acquisition element **30** when the ultrasonic array probe **10** is moved on the surface of the inspection object **200** along the X-axis direction (movement direction). The image display element **70** displays the C-scan image created by the image creation element **60**.

[0095] FIG. **10** is a diagram illustrating an example of a C-scan image displayed on the image display element **70**. In the grayscale image illustrated in FIG. **10**, the darker color indicates the smaller differential response value, and the lighter color indicates the larger differential response value. Areas AR**1**, AR**2**, AR**3**, and AR**4** illustrated in FIGS. **9** and **10** indicate areas on the XY plane of the inspection object **200**. The areas AR**1**, AR**2**, AR**3**, and AR**4** respectively correspond to the positions of defects DF**1**, DF**2**, DF**3**, and DF**4** present in the area where the adhesive **230** is disposed. From the C-scan image illustrated in FIG. **10**, it is possible to visually recognize at which position on the XY plane of the inspection object **200** the defect DF is present.

[0096] FIG. **11** is a diagram illustrating an example of a C-scan image displayed on the image display element **70** when the voltage application element **20** switches the voltage value applied to the ultrasonic elements **11***a* to **11***p*. Images IM**1**, IM**2**, IM**3**, IM**4**, and IM**5** illustrated in FIG. **11** are C-scan images when the voltage application element **20** applies a first voltage V**1**, a second voltage V**2**, a third voltage V**3**, a fourth voltage V**4**, and a fifth voltage V**5**. There is a relationship of the first voltage V**1**<the second voltage V**2**<the third voltage V**3**<the fourth voltage V**4**<the fifth voltage V**5**.

[0097] As illustrated in FIG. **11**, in the image IM**1** obtained when the first voltage V**1** is applied, the color is the darkest in almost all the areas of the inspection object **200**, indicating that the differential response value is 0 or a minute value. On the other hand, in the image IM**2** obtained when the second voltage V**2** is applied, the color is lighter than in the image IM**1** in a part of the areas of the inspection object **200**. This is because the differential response value has increased in the part of the areas of the inspection object **200**.

[0098] Then, as the voltage applied to the ultrasonic elements **11***a* to **11***p* is increased to the third voltage V**3**, the fourth voltage V**4**, and the fifth voltage V**5**, the differential response value at each position on the XY plane increases, and the color of a part of the areas of the inspection object **200** becomes even lighter. In the present embodiment, the opening width of the defect DF in the inspection object **200** can be measured by the measurement element **40** by focusing on such a change in the color density.

[0099] The operations and effects of the ultrasonic defect detection apparatus **100** of the present embodiment described above will be described.

[0100] According to the ultrasonic defect detection apparatus **100** of the present embodiment, when the voltage application element **20** executes the voltage application operation including the first operation and the second operation, the acquisition element **30** acquires a differential response value that is a difference between the first response value received by the ultrasonic array probe **10** in the first operation and the second response value obtained by adding a plurality of response values received by the ultrasonic array probe **10** in the second operation.

[0101] In the case of a defect exhibiting linear response characteristics in which the magnitude of a response value of reflected ultrasonic waves is proportional to the magnitude of the amplitude of ultrasonic waves transmitted from the ultrasonic elements, the differential response value is zero or a minute value. On the other hand, in the case of a defect exhibiting non-linear response characteristics in which the magnitude of a response value of reflected ultrasonic waves is not proportional to the magnitude of the amplitude of ultrasonic waves transmitted from the ultrasonic elements, the differential response value increases as the magnitude of the amplitude increases. The defect having non-linear response characteristics exhibits a linear response when the amplitude is small, but exhibits non-linear response characteristics when the amplitude increases.

[0102] Thus, the ultrasonic defect detection apparatus **100** of the present embodiment is configured to measure the opening width of the defect DF in the inspection object **200** based on a plurality of the differential response values acquired by the acquisition element **30** when the voltage application element **20** executes the voltage application operation at a plurality of the predetermined voltages having different voltage values. For example, when the voltage application element **20** executes the voltage application operation at the plurality of predetermined voltages while increasing the voltage value, the voltage value of the predetermined voltage at which the differential response value starts to increase is determined, whereby the opening width corresponding to the determined voltage value can be output as a measurement value.

[0103] Further, according to the ultrasonic defect detection apparatus **100** of the present embodiment, the storage element **50** stores a table associating a voltage value of a predetermined voltage applied by the voltage application element **20** when a differential response value acquired by the acquisition element **30** becomes a predetermined threshold value (e.g., a value reliably indicating that a non-linear response is exhibited) and an opening width of the defect DF in the inspection object **200**. Then, the measurement element **40** can measure the opening width based on the voltage value of the predetermined voltage applied by the voltage application element **20** when the differential response value acquired by the acquisition element **30** becomes the predetermined threshold value and the table stored in the storage element **50**.

[0104] According to the ultrasonic defect detection apparatus **100** of the present embodiment, each of a response value received by applying the predetermined voltage to the odd-numbered first element group and a response value received by applying the predetermined voltage to the even-numbered second element group is half a response value received by applying the predetermined voltage to all the elements. Thus, when the first response value received in the first operation exhibits non-linear response characteristics, the differential response value can be acquired such that each response value received when the predetermined voltage is applied to the first element group or the second element group exhibits linear response characteristics.

[0105] According to the ultrasonic defect detection apparatus **100** of the present embodiment, by creating a C-scan image with the image creation element **60**, an image of the inspection object **200** along the movement direction can be displayed, making it possible to easily recognize a position in the movement direction at which a defect has occurred.

Second Embodiment

[0106] Next, the ultrasonic defect detection apparatus **100** according to a second embodiment of the present disclosure will be described. The present embodiment is a modification of the first embodiment, and is assumed to be the same as the first embodiment unless otherwise described below.

[0107] In the ultrasonic defect detection apparatus **100** of the first embodiment, the voltage application element **20** executes the second operation of dividing the ultrasonic elements **11***a* to **11***p* into the even-numbered first element group and the odd-numbered second element group and applying a predetermined voltage to each element group at different timings. In contrast, in the ultrasonic defect detection apparatus **100** of the present embodiment, the voltage application element **20** applies a predetermined voltage to each of the ultrasonic elements **11***a* to **11***p* at different timings.

[0108] FIG. **12** is a flowchart illustrating the voltage application operation executed by the voltage application element **20**. FIG. **13** is a graph showing a relationship between an amplitude of ultrasonic waves and a response value acquired by the acquisition element **30**.

[0109] As illustrated in FIG. **12**, in step S**501**, the voltage application element **20** executes a first operation of simultaneously applying a predetermined voltage to all the ultrasonic elements **11***a* to **11***p*. Here, "simultaneously applying" means continuously performing an operation of applying a voltage pulse to all the ultrasonic elements **11***a* to **11***p* while delaying the voltage pulse applied to the ultrasonic elements **11***a* to **11***p* by delay times.

[0110] In step S**502**, the voltage application element **20** executes a second operation of applying a predetermined voltage to each of the ultrasonic elements **11***a* to **11***p* at different timings. The second operation is configured such that the predetermined voltage is applied to only one ultrasonic element and a response value of a reflected wave of an ultrasonic wave transmitted from the one ultrasonic element is acquired with the acquisition element **30** at all the ultrasonic elements **11***a* to **11***p*, and this operation is repeated by the number of the ultrasonic elements.

[0111] When the voltage application element **20** executes the first operation, the acquisition element **30** of the present embodiment acquires a response value (first response value) obtained by performing a binning process on the output values from the ultrasonic elements **11***a* to **11***p* with respect to the reflected waves of the ultrasonic waves transmitted by the ultrasonic elements **11***a* to **11***p*. When the voltage application element **20** executes the second operation, the acquisition element **30** repeats an operation of acquiring a response value obtained by performing a binning process on the output values from the ultrasonic elements **11***a* to **11***p* with respect to the reflected waves of the ultrasonic waves transmitted by the ultrasonic elements **11***a* to **11***p* by the number of the ultrasonic elements, thereby obtaining an added response value (second response value).

[0112] Then, the acquisition element **30** acquires a differential response value which is a difference between the first response value and the second response value. As in the first embodiment, the measurement element **40** measures the opening width of the defect DF in the inspection object **200** based on a plurality of the differential response values acquired by the acquisition element **30** when the voltage application element **20** executes the voltage application operation at a plurality of the predetermined voltages having different voltage values.

[0113] In FIG. **13**, an amplitude A**2** indicates an example of the amplitude of ultrasonic waves output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the first operation. On the other hand, an amplitude A**0** indicates an example of the amplitude of ultrasonic waves output from any one of the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the second operation.

[0114] In the case where the defect DF has linear response characteristics in which the magnitude of the response value of the reflected ultrasonic waves is proportional to the magnitude of the amplitude of the ultrasonic waves transmitted from the ultrasonic elements **11***a* to **11***p*, since the second operation uses 1/16 of the number of the ultrasonic elements used in the first operation, the amplitude A**0** is substantially 1/16 of the amplitude A**2**. The response value acquired by the acquisition element **30** with respect to the ultrasonic waves having the amplitude A**0** is F**0**, and the response value acquired by the acquisition element **30** with respect to the ultrasonic waves having the amplitude A**2** is F**2**. Since the response value F**0** is substantially 1/16 of the response value F**2**, the differential response value is zero or a minute value.

[0115] This is because, in the case of the defect DF having linear response characteristics, the first response value (F**2**) obtained by adding response values output from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the first operation is substantially the same as the second response value (F**0**×16) obtained by adding response values output one by one from the ultrasonic elements **11***a* to **11***p* when the voltage application element **20** executes the second operation.

[0116] As shown in FIG. **13**, the amplitude A**0** is extremely small at about 1/16 of the amplitude A**2**, and a difference in energy between the amplitude A**2** and the amplitude A**0** is large. Thus, the response value F**0** at the amplitude A**0** which serves as a reference for calculating the differential response value can be reliably made to have linear response characteristics. Since the response value F**0** exhibits linear response characteristics, an error in the differential response value is reduced, and an S/N ratio can be improved.

[0117] According to the ultrasonic defect detection apparatus **100** of the present embodiment, the predetermined voltage is applied to each of the predetermined number of ultrasonic elements **11***a* to **11***p* at different timings, and the second response value is obtained by adding the predetermined number of response values which are obtained by performing a binning process on the output values from the predetermined number of ultrasonic elements **11***a* to **11***p*. The response value F**0** received by applying the predetermined voltage to each of the ultrasonic elements **11***a* to **11***p* is substantially 1/16 of the response value received by applying the predetermined voltage to all the elements. Thus, when the first response value received in the first operation exhibits non-linear response characteristics, it is possible to improve the S/N ratio of the differential response value by making each response value received when the predetermined voltage is applied to each ultrasonic element to exhibit linear response characteristics.

Third Embodiment

[0118] Next, the ultrasonic defect detection apparatus **100** according to a third embodiment of the present disclosure will be described. The present embodiment is a modification of the second embodiment, and is assumed to be the same as the second embodiment unless otherwise described below.

[0119] In the ultrasonic defect detection apparatus **100** of the present embodiment, each of the plurality of ultrasonic elements **11***a* to **11***p* included in the ultrasonic array probe **10** includes an adjustment mechanism for adjusting a focal length. FIGS. **14** to **16** are front views illustrating a state in which an ultrasonic wave Uw is emitted from the single ultrasonic element **11***i* to the defect DF of the inspection object **200**.

[0120] Each of the plurality of ultrasonic elements **11***a* to **11***p* of the present embodiment includes an adjustment mechanism such as a piezoelectric element that bends the shape of an inside surface in accordance with the magnitude of a DC voltage applied from a DC voltage application element **80** to adjust a focal length from the ultrasonic array probe **10** to the location of a focal point. A DC voltage Vd**2** applied to the single ultrasonic element **11***i* from the DC voltage application element **80** illustrated in FIG. **15** is larger than a DC voltage Vd**1** applied to the single ultrasonic element **11***i* from the DC voltage application element **80** illustrated in FIG. **14**. In addition, a DC voltage Vd**3** applied to the single ultrasonic element **11***i* from the DC voltage application element **80** illustrated in FIG. **16** is larger than the DC voltage Vd**2** applied to the single ultrasonic element **11***i* from the DC voltage application element **80** illustrated in FIG. **15**.

[0121] As illustrated in FIGS. **14** to **16**, when the DC voltage applied to the single ultrasonic element **11***i* increases, the inside surfaces of the ultrasonic elements **11***a* to **11***p* are deformed to be concave surfaces, and the curvature radii of the concave surfaces decrease depending on the voltage. Thus, a focal length FD**2** in FIG. **15** is shorter than a focal length FD**1** in FIG. **14**, and a focal length FD**3** in FIG. **16** is shorter than the focal length FD**2** in FIG. **15**.

[0122] As illustrated in FIG. **14**, when the DC voltage applied to the single ultrasonic element **11***i* is Vd**1**, an irradiation width W of the ultrasonic wave Uw is constant regardless of the distance from the ultrasonic element **11***i*. On the other hand, as illustrated in FIGS. **15** and **16**, when the DC voltage applied to the single ultrasonic element **11***i* is Vd**2** or Vd**3**, the irradiation width W of the ultrasonic wave Uw becomes shorter as the distance from the ultrasonic element Ili becomes longer.

[0123] FIGS. **14** to **16** illustrate an example in which the DC voltage is applied from the DC voltage application element **80** to the ultrasonic element **11***i*, but the DC voltage can be selectively applied from the DC voltage application element **80** to any one of the ultrasonic elements **11***a* to **11***p*. By switching the ultrasonic element to which the DC voltage is to be applied by the DC voltage application element **80**, ultrasonic waves can be transmitted at an arbitrary position in the width direction WD.

[0124] For example, when the distance from the surface of the plate-like member **210** to an adhesive layer at which the adhesive **230** is present is known, the ultrasonic defect detection apparatus **100** of the present embodiment adjusts the DC voltage to be applied from the DC voltage application element **80** to the ultrasonic element so as to focus on the adhesive layer. Then, by switching the ultrasonic element to which the DC voltage is to be applied by the DC voltage application element **80**, ultrasonic waves can be transmitted from an arbitrary position in the width direction WD to the adhesive layer and reflected waves reflected by the adhesive layer can be received by the ultrasonic elements **11***a* to **11***p*.

[0125] For example, even when the distance from the surface of the plate-like member **210** to the adhesive layer at which the adhesive **230** is present is not known, the ultrasonic defect detection apparatus **100** of the present embodiment can change the DC voltage to be applied from the DC voltage application element **80** to the ultrasonic element so as to focus on the adhesive layer. FIG. **17** is a flowchart illustrating a process in which the DC voltage to be applied from the DC voltage application element **80** to the ultrasonic element is changed so as to focus on the adhesive layer and the voltage application element executes the voltage application operation.

[0126] In step S**601**, the DC voltage application element **80** applies the DC voltage Vd**1** to the single ultrasonic element Ili so that the irradiation width W of the ultrasonic wave Uw becomes constant regardless of the distance from the ultrasonic element **11***i*.

[0127] In step S**602**, the ultrasonic array probe **10** causes the voltage application element **20** to apply a predetermined voltage to the ultrasonic element **11***i* to transmit ultrasonic waves and measures a propagation time from when the ultrasonic element Ili transmits the ultrasonic waves to when the ultrasonic element **11***i* receives the ultrasonic waves.

[0128] In step S**603**, the ultrasonic array probe **10** detects the distance from the plate-like member **210** to the adhesive layer at which the ultrasonic waves are reflected, based on a known ultrasonic wave propagation speed in the plate-like member **210** and the propagation time measured in step S**602**. Then, the ultrasonic array probe **10** changes the DC voltage to be applied from the DC voltage application element **80** to the ultrasonic element so as to focus on the adhesive layer.

[0129] In step S**604**, the voltage application element **20** executes a first operation of simultaneously applying a predetermined voltage to all the ultrasonic elements **11***a* to **11***p*. Here, "simultaneously applying" means continuously performing an operation of applying a voltage pulse to all the ultrasonic elements **11***a* to **11***p* while delaying the voltage pulse applied to the ultrasonic elements **11***a* to **11***p* by delay times.

[0130] In step S**605**, the voltage application element **20** executes a second operation of applying a predetermined voltage to each of the ultrasonic elements **11***a* to **11***p* at different timings. The second operation is configured such that the predetermined voltage is applied to only one ultrasonic element and a response value of a reflected wave of an ultrasonic wave transmitted from the one ultrasonic element is acquired with the acquisition element **30** at all the ultrasonic elements **11***a* to **11***p*, and this operation is repeated by the number of the ultrasonic elements.

[0131] As described above, for example, even when the distance from the surface of the plate-like member **210** to the adhesive layer at which the adhesive **230** is present is not known, the ultrasonic defect detection apparatus **100** of the present embodiment can appropriately measure the opening width of the defect DF formed at the adhesive layer by changing the DC voltage to be applied from the DC voltage application element **80** to the ultrasonic element so as to focus on the adhesive layer.

[0132] According to the ultrasonic defect detection apparatus **100** of the present embodiment, the adjustment mechanisms included in the ultrasonic elements **11***a* to **11***p* adjust the focal lengths of the respective ultrasonic elements, whereby the energy of the ultrasonic elements is concentrated on the focal points to obtain high response values, and the S/N ratio of the differential response value can be improved.

[0133] The ultrasonic defect detection apparatus and the ultrasonic defect detection method described in the embodiments described above are grasped as follows, for example.

[0134] An ultrasonic defect detection apparatus according to a first aspect of the present disclosure includes:

- **[0135]** an ultrasonic array probe (**10**) including a predetermined number of ultrasonic elements arranged along a predetermined direction, each of the ultrasonic elements transmitting ultrasonic waves of a predetermined frequency to an inspection object (**200**) and receiving the ultrasonic waves of the predetermined frequency reflected by the inspection object;
- **[0136]** a voltage application element (**20**) executing a voltage application operation, the voltage application operation including a first operation of simultaneously applying a predetermined voltage to the predetermined number of ultrasonic elements, and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings;
- **[0137]** an acquisition element (**30**) acquiring a differential response value, the differential response value being a difference between a first response value of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe at different timings in the second operation; and
- **[0138]** a measurement element (**40**) measuring an opening width of a defect in the inspection object based on a plurality of the differential response values acquired by the acquisition element when the voltage application element executes the voltage application operation at a plurality of the predetermined voltages having different voltage values.

[0139] According to the ultrasonic defect detection apparatus according to the first aspect of the present disclosure, when the voltage application element executes the voltage application operation including the first operation and the second operation, the acquisition element acquires a differential response value that is a difference between the first response value received by the ultrasonic array probe in the first operation and the second response value obtained by adding a plurality of response values received by the ultrasonic array probe in the second operation.

[0140] In the case of a defect exhibiting linear response characteristics in which the magnitude of a response value of reflected ultrasonic waves is proportional to the magnitude of the amplitude of ultrasonic waves transmitted from the ultrasonic elements, the differential response value is zero or a minute value. On the other hand, in the case of a defect exhibiting non-linear response characteristics in which the magnitude of a response value of reflected ultrasonic waves is not proportional to the magnitude of the amplitude of ultrasonic waves transmitted from the ultrasonic elements, the differential response value increases as the magnitude of the amplitude increases. The defect having non-linear response characteristics exhibits a linear response when the amplitude is small, but exhibits non-linear response characteristics when the amplitude increases.

[0141] Thus, the ultrasonic defect detection apparatus according to the first aspect of the present disclosure is configured to measure the opening width of a defect in the inspection object based on a plurality of the differential response values acquired by the acquisition element when the voltage application element executes the voltage application operation at a plurality of the predetermined voltages having different voltage values. For example, when the voltage application element executes the voltage application operation at the plurality of predetermined voltages while increasing the voltage value, the voltage value of the predetermined voltage at which the differential response value starts to increase is determined, whereby the opening width corresponding to the determined voltage value can be output as a measurement value.

[0142] An ultrasonic defect detection apparatus according to a second aspect of the present disclosure is the ultrasonic defect detection apparatus of the first aspect, further including a storage element storing a table associating a voltage value of the predetermined voltage applied by the voltage application element when the differential response value acquired by the acquisition element becomes a predetermined threshold value and the opening width of the defect in the inspection object, in which the voltage application element switches the voltage value of the predetermined voltage such that the differential response value acquired by the acquisition element becomes the predetermined threshold value and executes the voltage application operation a plurality of times, and the measurement element measures the opening width based on the voltage value of the predetermined voltage applied by the voltage application element when the differential response value acquired by the acquisition element becomes the predetermined threshold value and the table stored in the storage element.

[0143] According to the ultrasonic defect detection apparatus according to the second aspect of the present disclosure, the storage element stores the table associating the voltage value of the predetermined voltage applied by the voltage application element when the differential response value acquired by the acquisition element becomes the predetermined threshold value (e.g., a value reliably indicating that a non-linear response is exhibited) and the opening width of the defect in the inspection object. Then, the measurement element can measure the opening width based on the voltage value of the predetermined voltage applied by the voltage application element when the differential response value acquired by the acquisition element becomes the predetermined threshold value and the table stored in the storage element.

[0144] An ultrasonic defect detection apparatus according to a third aspect of the present disclosure is the ultrasonic defect detection apparatus of the first aspect or the second aspect, in which the second operation is an operation of applying the predetermined voltage to a first element group including odd-numbered elements from one end in the predetermined direction among the predetermined number of ultrasonic elements and a second element group including even-numbered elements from the one end in the predetermined direction among the predetermined number of ultrasonic elements at different timings.

[0145] According to the ultrasonic defect detection apparatus according to the third aspect of the present disclosure, each of a response value received by applying the predetermined voltage to the odd-numbered first element group and a response value received by applying the predetermined voltage to the even-numbered second element group is half a response value received by applying the predetermined voltage to all the elements. Thus, when the first response value received in the first operation exhibits non-linear response characteristics, the differential response value can be acquired such that each response value received when the predetermined voltage is applied to the first element group or the second element group exhibits linear response characteristics.

[0146] An ultrasonic defect detection apparatus according to a fourth aspect of the present disclosure is the ultrasonic defect detection apparatus of any one of the first to third aspects, in which the second operation is an operation of applying the predetermined voltage to each of the predetermined number of ultrasonic elements at different timings.

[0147] According to the ultrasonic defect detection apparatus according to the fourth aspect of the present disclosure, the predetermined voltage is applied to each of the predetermined number of ultrasonic elements at different timings, and the second response value is obtained by adding a response value received by each of the predetermined number of ultrasonic elements. The response value received by applying the predetermined voltage to each of the ultrasonic elements is (1/the predetermined number) of the response value received by applying the predetermined voltage to all the elements. Thus, when the first response value received in the first operation exhibits non-linear response characteristics, it is possible to improve the S/N ratio of the differential response value by making each response value received when the predetermined voltage is applied to each of the ultrasonic elements to reliably exhibit linear response characteristics.

[0148] An ultrasonic defect detection apparatus according to a fifth aspect of the present disclosure is the ultrasonic defect detection apparatus of the fourth aspect, in which each of the ultrasonic elements includes an adjustment mechanism that adjusts a focal length.

[0149] According to the ultrasonic defect detection apparatus according to the fifth aspect of the present disclosure, the adjustment mechanism adjusts the focal length of each of the ultrasonic elements, whereby the energy of the ultrasonic elements is concentrated on focal points to obtain high response values, and the S/N ratio of the differential response value can be improved.

[0150] An ultrasonic defect detection apparatus according to a sixth aspect of the present disclosure is the ultrasonic defect detection apparatus of the fifth aspect, in which the adjustment mechanism adjusts the focal length in accordance with a propagation time from when the ultrasonic element transmits ultrasonic waves to when the ultrasonic element receives the ultrasonic waves.

[0151] According to the ultrasonic defect detection apparatus according to the sixth aspect, since the adjustment mechanism adjusts the focal length in accordance with the propagation time from when the ultrasonic element transmits the ultrasonic waves to when the ultrasonic element receives the ultrasonic waves, for example, even when the distance from a surface of the inspection object to the defect is not known, the opening width of the defect can be appropriately measured by adjusting the focal length so as to focus on the defect.

[0152] An ultrasonic defect detection apparatus according to a seventh aspect of the present disclosure is the ultrasonic defect detection apparatus of any one of the first to the sixth aspects, further including an image creation element (**60**) that creates a C-scan image from the differential response value acquired by the acquisition element when the ultrasonic array probe is moved on the surface of the inspection object along a movement direction intersecting the predetermined direction.

[0153] According to the ultrasonic defect detection apparatus according to the seventh aspect of the present disclosure, by creating a C-scan image with the image creation element, an image of the inspection object along the movement direction can be displayed, making it possible to easily recognize a position in the movement direction at which a defect has occurred.

[0154] An ultrasonic defect detection method according to an eighth aspect of the present disclosure is an ultrasonic defect detection method for measuring an opening width of a defect in an inspection object with an ultrasonic defect detection apparatus, the ultrasonic defect detection apparatus including an ultrasonic array probe including a predetermined number of ultrasonic elements arranged along a predetermined direction, each of the ultrasonic elements transmitting ultrasonic waves of a predetermined frequency to the inspection object and receiving the ultrasonic waves of the predetermined frequency reflected by the inspection object, the ultrasonic defect detection method including:

- **[0155]** a voltage application process of executing a voltage application operation, the voltage application operation including a first operation of simultaneously applying a predetermined voltage to the predetermined number of ultrasonic elements, and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings;
- **[0156]** an acquisition process of acquiring a differential response value, the differential response value being a difference between a first response value of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe at different timings in the second operation; and
- **[0157]** a measurement process of measuring the opening width of the defect in the inspection object based on a plurality of the differential response values acquired by the acquisition process when the voltage application process executes the voltage application operation at a plurality of the predetermined voltages having different voltage values.

[0158] According to the ultrasonic defect detection method according to the eighth aspect of the present disclosure, when the voltage application operation including the first operation and the second operation is executed in the voltage application process, the differential response value that is a difference between the first response value received by the ultrasonic array probe in the first operation and the second response value obtained by adding the plurality of response values received by the ultrasonic array probe in the second operation is acquired in the acquisition process.

[0159] In the case of exhibiting linear response characteristics in which the magnitude of a response value of reflected ultrasonic waves is proportional to the magnitude of the amplitude of transmitted ultrasonic waves, the differential response value is zero or a minute value. On the other hand, in the case of exhibiting non-linear response characteristics in which the magnitude of a response value of reflected ultrasonic waves is not proportional to the magnitude of the amplitude of transmitted ultrasonic waves, the differential response value increases as the magnitude of the amplitude increases. In the case of a defect having non-linear response characteristics in which a response value of received ultrasonic waves in not proportional to the magnitude of the amplitude of transmitted ultrasonic waves, a linear response is exhibited when the amplitude is small, but a non-linear response is exhibited when the amplitude increases.

[0160] Thus, the ultrasonic defect detection method according to the eighth aspect of the present disclosure is configured to measure the opening width of a defect in the inspection object based on a plurality of the differential response values acquired in the acquisition process when the voltage application operation is executed at a plurality of the predetermined voltages having different voltage values in the voltage application process. For example, when the voltage application operation is executed at the plurality of predetermined voltages while increasing the voltage value in the voltage application process, the voltage value of the predetermined voltage at which the differential response value starts to increase is determined, whereby the opening width corresponding to the determined voltage value can be output as a measurement value.

REFERENCE SIGNS LIST

- **[0161]** **10** Ultrasonic array probe
- **[0162]** **11***a*, **11***b*, **11***c*, **11***d*, **11***e*, **11***f*, **11***g*, **11***h*, **11***i*, **11***j*, **11***k*, **11***l*, **11***m*, **11***n*, **11***o*, **11***p*
- **[0163]** Ultrasonic element
- **[0164]** **20** Voltage application element
- **[0165]** **30** Acquisition element
- **[0166]** **40** Measurement element
- **[0167]** **50** Storage element
- **[0168]** **60** Image creation element
- **[0169]** **70** Image display element
- **[0170]** **80** DC voltage application element
- **[0171]** **100** Ultrasonic defect detection apparatus
- **[0172]** **200** Inspection object
- **[0173]** **210** Plate-like member
- **[0174]** **220** Plate-like member
- **[0175]** **230** Adhesive
- **[0176]** A**0**, A**1**, A**2** Amplitude
- **[0177]** AR**1**, AR**2**, AR**3**, AR**4** Area

[0178] DF, DF**1**, DF**2**, DF**3**, DF**4** Defect
[0179] FD**1**, FD**2**, FD**3** Focal length
[0180] Fd Differential response value
[0181] IM**1**, IM**2**, IM**3**, IM**4**, IM**5** Image
[0182] Uw Ultrasonic wave
[0183] WD Width direction

1. An ultrasonic defect detection apparatus comprising:
- an ultrasonic array probe including a predetermined number of ultrasonic elements arranged along a predetermined direction, each of the ultrasonic elements being configured to transmit ultrasonic waves of a predetermined frequency to an inspection object and receive the ultrasonic waves of the predetermined frequency reflected by the inspection object;
- a voltage application element configured to execute a voltage application operation, the voltage application operation including a first operation of simultaneously applying a predetermined voltage to the predetermined number of ultrasonic elements, and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings;
- an acquisition element configured to acquire a differential response value, the differential response value being a difference between a first response value of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe at different timings in the second operation; and
- a measurement element configured to measure an opening width of a defect in the inspection object based on a plurality of the differential response values acquired by the acquisition element when the voltage application element executes the voltage application operation at a plurality of the predetermined voltages having different voltage values.

2. The ultrasonic defect detection apparatus according to claim **1**, further comprising a storage element configured to store a table associating a voltage value of the predetermined voltage applied by the voltage application element when the differential response value acquired by the acquisition element becomes a predetermined threshold value and the opening width of the defect in the inspection object, wherein
- the voltage application element switches the voltage value of the predetermined voltage such that the differential response value acquired by the acquisition element becomes the predetermined threshold value and executes the voltage application operation a plurality of times, and
- the measurement element measures the opening width based on the voltage value of the predetermined voltage applied by the voltage application element when the differential response value acquired by the acquisition element becomes the predetermined threshold value and the table stored in the storage element.

3. The ultrasonic defect detection apparatus according to claim **1**, wherein the second operation is an operation of applying the predetermined voltage to a first element group and a second element group at different timings, the first element group including odd-numbered elements from one end in the predetermined direction among the predetermined number of ultrasonic elements, the second element group including even-numbered elements from the one end in the predetermined direction among the predetermined number of ultrasonic elements.

4. The ultrasonic defect detection apparatus according to claim **1**, wherein the second operation is an operation of applying the predetermined voltage to each of the predetermined number of ultrasonic elements at different timings.

5. The ultrasonic defect detection apparatus according to claim **4**, wherein each of the ultrasonic elements includes an adjustment mechanism configured to adjust a focal length.

6. The ultrasonic defect detection apparatus according to claim **5**, wherein the adjustment mechanism adjusts the focal length in accordance with a propagation time from when the ultrasonic element transmits ultrasonic waves to when the ultrasonic element receives the ultrasonic waves.

7. The ultrasonic defect detection apparatus according to claim **1**, further comprising an image creation element configured to create a C-scan image from the differential response value acquired by the acquisition element when the ultrasonic array probe is moved on a surface of the inspection object along a movement direction intersecting the predetermined direction.

8. An ultrasonic defect detection method for measuring an opening width of a defect in an inspection object with an ultrasonic defect detection apparatus,

the ultrasonic defect detection apparatus comprising:
- an ultrasonic array probe including a predetermined number of ultrasonic elements arranged along a predetermined direction, each of the ultrasonic elements being configured to transmit ultrasonic waves of a predetermined frequency to the inspection object and receive the ultrasonic waves of the predetermined frequency reflected by the inspection object,

the ultrasonic defect detection method comprising:
- a voltage application process of executing a voltage application operation, the voltage application operation including a first operation of simultaneously applying a predetermined voltage to the predetermined number of ultrasonic elements, and a second operation of dividing the predetermined number of ultrasonic elements into a plurality of element groups and applying the predetermined voltage to each of the element groups at different timings;
- an acquisition process of acquiring a differential response value, the differential response value being a difference between a first response value of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe in the first operation and a second response value obtained by adding a plurality of response values of the ultrasonic waves of the predetermined frequency received by the ultrasonic array probe at different timings in the second operation; and
- a measurement process of measuring the opening width of the defect in the inspection object based on a plurality of the differential response values acquired in the acquisition process when the voltage application operation is executed at a plurality of the predetermined voltages having different voltage values in the voltage application process.

* * * * *