



(51) International Patent Classification:

G01N 29/04 (2006.01) *G01N 29/24* (2006.01)*B06B 1/08* (2006.01) *G01N 29/44* (2006.01)*G01N 27/72* (2006.01) *H01F 7/02* (2006.01)*G01N 27/87* (2006.01)

(21) International Application Number:

PCT/GB2017/052869

(22) International Filing Date:

26 September 2017 (26.09.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1705837.1

11 April 2017 (11.04.2017)

GB

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,

(54) Title: ELECTROMAGNETIC ACOUSTIC TRANSDUCER BASED RECEIVER

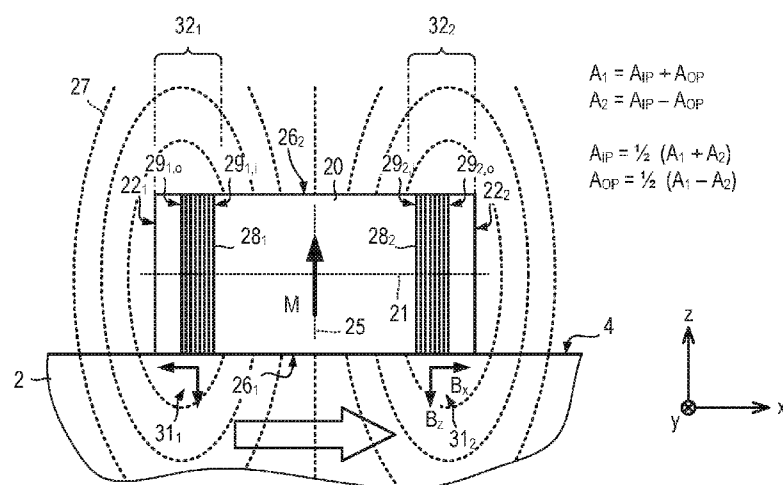


Fig. 3

(57) **Abstract:** An electromagnetic acoustic transducer (EMAT) based receiver is disclosed. The EMAT-based receiver comprises a permanent magnet (20) which extends along a first axis (21) between first and second ends (22₁, 22₂) and which is magnetised along a second, transverse axis (25) and first and second coils (28₁, 28₂) wound around the permanent magnet. The first and second coils are wound around the first axis and are spaced apart along the first axis. The first and second coils are wound close to the first and second ends respectively such that, when the receiver is presented to a sample (2), the first and second coils are located next to first and second surface regions (31₁, 31₂) of the sample in which magnetic flux (27) has first and second non-zero components along the first and second axes respectively.



KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

Electromagnetic acoustic transducer based receiver

Field of the Invention

The present invention relates to an electromagnetic acoustic transducer (EMAT) based receiver for sensing surface acoustic waves (SAWs) in sample and to a sensor which includes a transmitter from generating SAWs in a sample (which may be an EMAT-based transmitter) and an EMAT-based receiver.

Background

Inspection of surface-breaking defects is important in a number of applications such as, for example, monitoring integrity of rails or engine blades. To measure the geometry of a defect, phased array techniques can be used and they generally provide excellent imaging results. However, phased array techniques involve making contact with the sample under test and using couplant fill air gaps. If there is a coating on the sample, it must be removed prior to testing. Moreover, phased array techniques tend to be expensive and require complicated setup (particularly if generating Rayleigh waves), as well as complex analysis routines to fully optimise the results.

Often, however, an operator may only have access to the side containing the defects and so techniques have been developed for use in these circumstances, such as the so-called "satellite pulse" technique, whereby a shear wave is bounced off the far side of the sample and reflections back along the same path from any defects are detected. This can measure defects as small as 5% through-wall thickness. A near side detection and sizing transducer looks for reflections of a longitudinal wave propagating at a very shallow angle to the surface. Although this arrangement overcomes some of the issues of same-side inspection, it requires a complicated set-up.

The use of surface waves for inspection can make crack characterisation much simpler.

Although electromagnetic acoustic transducers (EMATs) are less efficient transducers, they overcome many of these issues. For example, EMATs can be used when there are thin, electrically insulating coatings.

Various EMAT designs have been considered to optimise generation and detection of particular wave types, such as bulk, shear, and SAW, to enhance the capabilities of non-contact non-destructive testing. Linear coil designs are predominantly used for

detection. More complicated designs have been developed, such as a butterfly-shaped detection coil and a double coil on a Halbach magnet for pipe monitoring using shear waves. Different shapes of coils, such as pancake-, meander-, rectangular- and racetrack-shaped coils, different magnetic field configurations and the use of pulsed magnetic fields have been considered for defect monitoring and thickness gauging. A combination of laser generation and EMAT detection has been used to detect in-plane components of a variety of wavemodes, such as shear, Lamb, longitudinal and mode-converted waves.

10 EMAT designs for detecting in-plane or out-of-plane components of ultrasonic waves are becoming more widely known due to recent developments in EMAT design. These arrangements involve using two separate detectors which makes it is difficult to ensure that signals are correctly identified as being from the same defect.

15 Processing methods for defect detection and thickness gauging are usually based on generating an ultrasonic wave and looking for reflections from imperfections in the sample such as cracks, voids and other defects. Recently there has been interest in the use of SAWs, in particular Rayleigh waves, for analysis of surface-breaking defects. These types of defects are challenging to detect and characterise using contact ultrasonic transducers. However, transmission of the waves underneath defects can be used to characterise the extent of the cracking into the material.

An example of this approach involves generating Rayleigh or Lamb waves on a sample and analysing reflected and transmitted waves. By using a broadband pulse, the depth of a surface-breaking defect that penetrates into a material can be measured.

Reference is made to R. S. Edwards, S. Dixon and X. Jian: "Depth gauging of defects using low frequency wideband Rayleigh waves", Ultrasonics, volume 44, pages 93-98 (2006).

30 Constructive interference of incident waves and those resulting from reflection and mode-conversion at a defect can be used as a clear indicator of the location of a defect. The behaviour of waves in the vicinity of a defect depends strongly on the defect geometry. By considering this and relative behaviours of in-plane and out-of-plane wave velocity, some features of the geometry of the defect can be identified. Reference is made to M. H. Rosli, B. Dutton and R. S. Edwards: "In-plane and out-of-plane measurements of Rayleigh waves using EMATs for characterising surface cracks",

NDT&E International, volume 49, pages 1 to 9 (2012), J. F. Hernandez-Valle, R. S. Edwards, B. Dutton, A. R. Clough and M. H. Rosli: "Laser ultrasonic characterisation of branched surface-breaking defects", NDT&E International, volume 68, pages 113 to 119 (2014) and R. S. Edwards, B. Dutton, A. R. Clough and M. H. Rosli "Enhancement of
5 ultrasonic surface waves at wedge tips and angled defects", Applied Physics Letters, volume 99, page 094104 (2011).

Summary

According to a first aspect of the present invention there is provided an electromagnetic acoustic transducer based receiver comprising a permanent magnet which extends between first and second ends along a first axis and which is magnetised along a second axis which is transverse (for example, perpendicular) to the first axis and first and second coils wound around the permanent magnet. The first and second coils are wound around the first axis and are spaced apart along the first axis. The first and second coils are wound close (or “proximate”) to the first and second ends respectively such that, when the receiver is presented to a sample (*e.g.* is placed next to the sample), the first and second coils are located next to first and second surface regions of the sample in which magnetic flux has first and second non-zero components along the first and second axes respectively.

The receiver is capable of extracting in-plane and out-of-plane components of surface acoustic waves in a sample disposed next to the receiver along the second axis.

The permanent magnet may comprise first and second opposite faces (or “poles”) running between the first and second ends and through which magnetic flux passes. Thus, when a face (*e.g.* the first face) of the permanent is presented to the sample, magnetic flux passes into a surface region of the sample and the magnetic flux in first and second regions of the surface regions which lie proximate to the first and ends have first and second components along the first and second axes respectively.

The first and second coils may be contained within respective first and second end sections of the magnet lying at the first and second ends of the magnet respectively and extending no more than 4 mm from the first and second ends and preferably no more than 3 mm from the first and second ends. The coils are preferably separated by at least 1 mm, *i.e.* there is a gap of at least 1 mm between inner edges of the coil.

The receiver may comprise at least one additional permanent magnet, preferably two additional permanent magnets, stacked on top of the permanent magnet along the second axis.

According to a second aspect of the present invention there is provided a sensor comprising a transmitter for generating ultrasonic surface acoustic waves in a sample

and a receiver according to claim 1 or 2, spaced apart from the transmitter along the sample along the first axis, for measuring surface acoustic waves in the sample.

5 The transmitter may be an electromagnetic acoustic transducer. The transmitter electromagnetic acoustic transducer may be a racetrack-type electromagnetic acoustic transducer. Alternatively, other arrangements for generating waves can used, such as other electromagnetic acoustic transducer designs, a laser ultrasound source or a piezoelectric transducer.

10 The receiver may be a first receiver and the sensor may further comprise a second receiver according to the first aspect of the present invention and the transmitter may be interposed between the first and second receivers.

15 This can help to reduce the need for a second scan if there are multiple or inclined cracks.

The sensor may comprise at least two rows arranged along a third axis which is transverse (for example, perpendicular) to the first and second axes. Each row may comprise a transmitter and a receiver. Each row may comprise a transmitter and first and second receivers wherein the transmitter is interposed between the first and
20 second receivers.

This can help to cover a larger area while scanning and/or to reduce the need for a second scan if there are multiple or inclined cracks.

25 According to a third aspect of the present invention there is provided a measurement system comprising a pulse generator configured to cause the transmitter to generate the surface acoustic waves in a sample, a sensor according to the second aspect of the present invention, wherein the first and second coils generate first and second time varying signals respectively and a signal processing system configured to generate first
30 and second compensated time-varying signals by applying a time shift to at least one of the first and second time-varying signals respectively, to calculate an in-plane signal by summing the first and second compensated time-varying signals, and to calculate an out-of-plane signal taking a difference between the first and second compensated time-varying signals.

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The signal processing system may be further configured to display and/or to store the in-plane signal and/or out-of-plane signal.

5 According to a fourth aspect of the present invention there is provided a method of processing surface acoustic wave signals comprising receiving first and second time varying signals, generating first and second compensated time-varying signals by applying a time shift to at least one of the first and second time-varying signals respectively, calculating an in-plane signal by summing the first and second compensated time-varying signals and calculating an out-of-plane signal taking a
10 difference between the first and second compensated time-varying signals.

According to a fifth aspect of the present invention there is provided a computer program which, when executed by a computer, causes the computer to perform a method according to the fourth aspect.

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According to a sixth aspect of the present invention there is provided a computer program product comprising a computer-readable medium, for example a non-transitory computer-readable medium, storing a computer program according to the fifth aspect.

Brief Description of the Drawings

Certain embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

- Figure 1 is a schematic block diagram of an inspection system which includes a sensor for generating and detecting surface acoustic waves in a sample and which includes an EMAT-based receiver, and a computer system for analysing detected signals;
- Figure 2 is a perspective view of an EMAT-based receiver when presented to a sample;
- Figure 3 is side view of the EMAT-based receiver shown in Figure 2;
- Figure 4 is a side view of a modified EMAT-based receiver;
- Figure 5 is a schematic block diagram of a computer system;
- Figure 6 is process flow diagram of a method of inspection;
- Figure 7 shows a graph of measured signal amplitudes and a time-shifted measured signal amplitude plotted against time for a Rayleigh wave propagating through aluminium;
- Figure 8 shows a graph of measured and calculated in-plane and out-of-plane signal amplitudes plotted against time for a Rayleigh wave propagating through aluminium;
- Figure 9 shows a graph of measured and calculated in-plane and out-of-plane signal amplitudes plotted against time for an S_0 Lamb wave propagating through aluminium; and
- Figure 10 shows a graph of measured and calculated in-plane and out-of-plane signal amplitudes plotted against time for an A_0 Lamb wave propagating through aluminium;
- Figure 11 is a schematic block diagram of a sensor comprising an array of transducers for generating ultrasonic surface acoustic waves and an array of EMAT-based receivers; and
- Figure 12 is process flow diagram of a simplified method of inspection.

Detailed Description of Certain Embodiments

Referring to Figure 1, an ultrasonic system 1 for inspecting an electrically-conductive sample 2, such as rail or engine blade, using ultrasonic surface acoustic waves 3 is shown.

The system 1 can be used to inspect a surface 4 of the sample 2 to identify, locate and/or characterise a crack 5, for example, in terms of penetration depth, d , and angle of the crack to the surface, θ . The sample surface 4 may be covered by an electrically-insulating coating 5, such as a coat of paint or plastic.

The system 1 includes an ultrasonic sensor 6 mounted to a positioning system 7, such as a motor-driven x-y stage, for moving the sensor 6 with respect to the sample 2. The ultrasonic sensor 6 comprises an ultrasonic transducer 8 (or “generator”), preferably in the form of an EMAT, for generating ultrasonic surface acoustic waves 2 in the sample 2 and a dual-coil EMAT-based receiver 9 for measuring ultrasonic surface acoustic waves 2 propagating in the sample 2. The generator 8 and receiver 9 are arranged in a line and are spaced apart along the line by a distance, s , in a range between 30 and 250 mm. In this case, the generator 8 and receiver 9 are spaced by 50 mm.

10 The ultrasonic sensor 6 can be withdrawably presented to the surface 4 of the sample 2 to inspect the sample 2 and can be moved over the surface 4 of the sample using the positioning system 7.

The system 1 includes a pulse generator 10 for driving the ultrasonic transducer 8 at a frequency in a range 50 kHz to 2 MHz. The system 1 includes amplifiers 11 for amplifying time-varying signals received from the dual-coil EMAT-based receiver 9, an acquisition device 12, for example in the form of an analogue-to-digital converter (ADC) or digital storage oscilloscope (DSO), for digitising the received signals received from the amplifier 11, and a computer system 13 for processing the received signals received from the acquisition device 12. The acquisition device 12 may be incorporated into the computer system 13, e.g. in the form of an ADC or DSO card or module.

Referring to Figures 2 and 3, the dual-coil EMAT-based receiver 9 comprises a box-shaped (or “rectangular cuboid”) permanent magnet 20. The permanent magnet 20 consists of neodymium-iron-boron (NdFeB) or other suitable magnetic material having a high remanent magnetization (e.g. compared to hard ferrite materials). The permanent magnet 20 extends along a first axis 21 (parallel to the x-axis) between first and second ends 22₁, 22₂. The permanent magnet 20 also extends along a second axis (parallel to the y-axis) between first and second sides 24₁ (the second side is not shown). Along a third axis 25 (parallel to the z-axis), the permanent magnet 20 lies between first and second faces 26₁, 26₂ (herein referred to as “lower and upper faces” respectively). The permanent magnet 20 is square in plan view and has a length, l of 8 mm, a width, w , of 8 mm and a thickness, h , of 4 mm. The permanent magnet 20 can have other geometries, aspect ratios and/or dimensions.

The permanent magnet 20 is magnetized along the axis 25 parallel to the z-axis which is normal to the lower and upper faces 26₁, 26₂. Thus, when the lower face 26₁ of the permanent magnet 20 placed on or against a sample 2, magnetic flux 27 passes into the sample 2. The first and second faces 26₁, 26₂ may also be referred to as “first and second poles”.

First and second linear coils 28₁, 28₂ are wound around the permanent magnet 20, around the first axis 21. The coils 28₁, 28₂ may be wound onto a coil former (not shown) and the permanent magnet 20 may be inserted into the former (not shown).
 10 The first and second coils 28₁, 28₂ are spaced apart along the permanent magnet 20, along the first axis 21, along and in line with the line that the generator 8 and receiver 9 are spaced.

The first and second coils 28₁, 28₂ are disposed close to the first and second ends 22₁, 22₂ respectively of the permanent magnet 20. Each coil 28₁, 28₂ comprises n turns of wire, and has a length, l_w , along the first axis 21 and a width, w_w , along the second axis 23, and are offset from the ends 22₁, 22₂ of the permanent magnet 20 by a distance, l_g . In this case, $n = 8$, $l_w = 1.2$ mm, $w_w = 8$ mm and $l_g = 1$ or 0.5 mm. The first and second coils 28₁, 28₂ are separated by a distance, l_s . The coils 28₁, 28₂ are placed the same
 20 distance from the ends 22₁, 22₂ of the permanent magnet 20. In other words, the coil positions are symmetrical about a centre point between the two ends of the permanent magnet 20. Each coil 28₁, 28₂ has an inner coil edge 29_{1,i}, 29_{2,i} and an outer coil edge 29_{1,o}, 29_{2,o}. The inner edge 29_{1,i}, 29_{2,i} lies further away from the end of the magnet (i.e. the end of the magnet closest to the coil) than the outer edge 29_{1,o}, 29_{2,o}.

25 The offset, l_g , preferably lies in the range $0 \text{ mm} \leq l_g \leq 1 \text{ mm}$ and more preferably $0 \text{ mm} \leq l_g \leq 0.5 \text{ mm}$. The length of the coil, l_w , depends on the frequency of the signal and can be chosen to obtain signal with sufficient signal-to-noise ratio. The width of the coil w_w can be chosen to obtain signal with sufficient signal-to-noise ratio and to be as
 30 small as possible to obtain sufficient spatial resolution. The coils 28₁, 28₂ are arranged such that $l_s > l_g$.

Referring also to Figure 4, one, two or more additional permanent magnets 20' having the same or similar geometry and dimensions as the permanent magnet 20 may be
 35 stacked on top of the permanent magnet 20 to form a stack 30. The magnetisations of the additional magnets 20' are orientated in the same direction as the permanent

magnet 20. This arrangement can be used to increase magnetic field strength and reduce fringing fields. The coils 28₁, 28₂, however, are preferably not wound around the additional permanent magnets 20. In other words, the coils 28₁, 28₂ are only wound around the permanent magnet 20 at the base of the stack 30. This arrangement can help to reduce coil impedance and the associated so-called “dead time” of the amplifier 11 (Figure 1).

Referring again to Figures 2 and 3, when the sensor 6 (Figure 1) is placed on or against the surface 4 of the sample 2, magnetic flux 27 (herein also referred to as “B field”) from the permanent magnet 20 enters into the sample 2 under the permanent magnet 20. The magnetic field 27 in the sample 2 has two magnetic field components, namely B_z and B_x.

As explained earlier, the coils 28₁, 28₂ are wound close (or “proximate”) to the ends 22₁, 22₂ of the permanent magnet 20. In particular, each coil 22₁, 22₂ is positioned over first and second surface regions 31₁, 31₂ of the sample 2 in which the magnetic flux 27 has sufficiently large, non-zero first and second components along the first and second axes, *i.e.* sufficiently large B_z and B_x. The relative values of the field components B_z and B_x may be expressed as αB_0 and $(1-\alpha)B_0$ where α lies between 0 and 1. Thus, α may take a value of between 0.2 and 0.8 (*i.e.* $0.2 \leq \alpha \leq 0.8$) or preferably between 0.4 and 0.6 (*i.e.* $0.4 \leq \alpha \leq 0.6$). In other words, the magnitudes of the components are similar or preferably about the same.

This can be achieved by positioning each coil 28₁, 28₂ such that the coil 28₁, 28₂ is contained within a respective section 32₁, 32₂ of the magnet 20 which extends from a respective end 22₁, 22₂ of the magnet. Herein, the sections 32₁, 32₂ are referred to as “end sections” of the magnet 20. The end sections 32₁, 32₂ may extend no more than 4 mm, and preferably no more than 3 mm, towards the middle of the magnet 20 from the ends 22₁, 22₂ of the magnet 20. Each coil 28₁, 28₂ is contained within a respective end section 32₁, 32₂, but there is a sufficient gap between the inner edge 29_{1,i}, 29_{2,i} of each coil 28₁, 28₂. The coils are separated by at least 1 mm. In other words, there is a gap of at least 1 mm between inner edges 29_{1,i}, 29_{2,i} of the coil. Thus, $(l_g + l_w) \leq 4\text{mm}$, $l_g \leq 1\text{mm}$ and $l_s \geq 1\text{mm}$.

The receiver 9 employs EMAT detection using the Lorentz force mechanism which involves generation of a current resulting from charged particles moving in a magnetic

field 27. The direction of the magnetic field 27 and the orientation of the coil 28₁, 28₂ determine which velocity component(s) is/are detected. Thus, for the dual-coil EMAT-based receiver 9, a field in the z-direction results in detection of in-plane velocities and a field in the x-direction results in detection of out-of-plane velocities.

5

First and second time-varying signal amplitudes $A_1(t)$, $A_2(t)$ are measured for the first and second coils 28₁, 28₂ respectively. Each signal contains a mix of the in-plane and out-of-plane components due to the presence of the two magnetic field components. As the x components of the magnetic field 27 are in opposite directions for the first and second coils 28₁, 28₂, this allows in-plane and out-of-plane velocity components to be extracted from the two signals.

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Referring to Figure 5, signal analysis and control is implemented in software on the computer system 13. The computer system 13 includes at least one processor 33, memory 34 and an input/output (I/O) interface 35 operatively connected by a bus 36. The I/O interface 35 is operatively connected to storage 37 in the form of a solid state and/or hard disc drive or drives, an interface 38 to removable storage 39 (such as a flash drive), one or more network interfaces 40. The computer system 13 also includes one or more displays 41 and one or more user input devices 42 (such as keyboards, mouse and/or a touch screen). Data processing software 43 and control software 44 are stored on the hard drive 37.

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Referring to Figures 1, 2, 3 and 6, a method of signal processing will now be described.

25

The sensor 6 is placed on or against the surface 4 of the sample 2. The computer system 13, automatically or under user control, causes the positioning system 7 to position the sensor 6 at a position p_i (step S1). The computer system 13 receives signals (that is signals from the coils 28₁, 28₂ via the amplifier 11 and acquisition device 12) for first and second coils 28₁, 28₂ (step S2).

30

Before in-plane and out-of-plane components of the signals can be extracted, a time delay, Δt , is introduced into one of the signals because the wave 3 propagating in the sample 2 will arrive at the first and second coils 28₁, 28₂ at different times due being separated by the distance, l_s (step S3).

35

The time delay, Δt , depends on the spatial coil separation, l_s , as well as on wave propagation velocity (which depends on the sample material and geometry). A calibration step, to determine the time delay, need only be performed once, namely after the coils 28₁, 28₂ are manufactured. A measurement using ultrasound behaviour
5 can provide a more accurate adjustment than measuring the coil separation using a ruler.

A time delay, Δt , that is necessary to achieve temporal overlap of the first and second signals is obtained using a configuration where the magnetic field is the same for both
10 coils. In the case where the detection coils 28₁, 28₂ are wound on the coil former (not shown) such that the coils 28₁, 28₂ can be removed from the magnet, this is achieved by inserting a magnet (not shown) into the coil former (not shown), ensuring that the magnet is much larger (i.e. longer) than the coil separation such that the magnetic field at each coil can be taken to be the same. The magnetic field is directed into the sample,
15 giving the in-plane velocity component. In the case where the detection coils 28₁, 28₂ are wound directly onto the permanent magnet 20, additional magnets (not shown) may be placed either side of the permanent magnet 20 to reduce the horizontal magnetic field component in the sample 2.

20 If this calibration is done on the same material and using the same ultrasonic wavemode which will be used for future tests (e.g. Rayleigh wave on a thick sample of aluminium), no further actions are necessary, and the measured time delay can be used directly in the calculations. If the receiver 9 is to be used on a variety of different materials and/or using Rayleigh and/or Lamb waves, then speed of the particular test
25 wave is used to calculate the spatial coil separation. This can then be converted back to time delay for other materials and/or other wavemodes. The wave velocity for the wavemode used for testing is measured with high precision by doing time-of-flight measurements at varying distances from the generating coil.

30 Figure 7 shows a Rayleigh wave in an aluminium sample measured by the two detection coils 28₁, 28₂, and the effect of a time delay of $\Delta t = 1.85 \mu s$. This time delay corresponds to a coil separation, l_s , (Figure 2) of 5.4 mm.

35 Once the time delay has been factored in, the in-plane and our-of-plane components of the signals are calculated by taking the sum and differences respectively of the two signals, namely:

$$A_{IP} = 1/2 (A_1 + A_2) \quad (1)$$

$$A_{OP} = 1/2 (A_1 - A_2) \quad (2)$$

5 where A_1 and A_2 are the amplitudes of the first and second time-varying signals suitably corrected using the time shift (step S6).

The computer system 13 applies a geometric shift (step S7) and the in-plane and out-of-plane components using equations (1) and (2) above (step S8).

10

Figure 8 shows the result extracting the in-plane and out-of-plane components using equations (1) and (2) above. In Figure 8, the result is labelled 'calculated from differential' and is compared measurements of in-plane and out-of-plane components measured using separate EMATs (not shown) arranged to detect in-plane or out-of-plane velocity components.

15

Figure 8 shows an S_0 Lamb wave mode for a frequency-thickness of 0.3 MHz.mm, measured on an aluminium plate. This mode should be substantially non-dispersive for the frequency bandwidth generated. The majority of the energy of the S_0 wavemode at this frequency-thickness is in in-plane motion and so the out-of-plane signals have been scaled by a factor of 2 to show the shape of the wave.

20

Figure 9 shows the A_0 Lamb wave mode, with the time delay calculated for a frequency-thickness of 0.15 MHz.mm. The dashed lines show the wave arrival time window for this frequency-thickness, identified using a sonogram. This mode is expected to be dispersive, hence different delays are required for different frequency-thicknesses. However, calculation of the time difference at a central frequency will enable identification of the chosen mode behaviour. For both Lamb wavemodes, the amplitude distribution between the in-plane and out-of-plane components is as expected.

30

Referring still to Figures 1, 2, 3 and 6, the computer system 13 builds an amplitude map for the in-plane and out-of-plane components (step S9).

The computer system 13 may, optionally, scan in the reverse direction (step S10). Thus, if a first scan is performed by moving the ultrasonic sensor 6 from a first position A to a second position B, a second scan, in the reverse direction, is performed by moving the

35

sensor 6 from the second position B to the first position A. For each scan, the receiver 9 is at the front.

5 The computer system 13 calculates transmission, enhancements, enhancement ratio (step S11), obtains crack position (step S12), obtains defect angle (step S13) and defect depth (step S14).

10 For characterising cracks, transmission coefficients can give a measure of the depth of the crack by looking at how much signal is blocked by a crack or which frequencies are blocked, while signal enhancement measured for the IP and OP velocity components when the EMAT is above a defect can give the angle of propagation into the material. This enhancement is due to interference between incident and reflected waves. For both of these measurements, an initial reference signal is measured on a section of sample which does not contain defects to give a comparison amplitude which can be
15 compared to wave amplitudes during the scan when either enhanced or reduced due to a defect. Using this process, the enhancement coefficients can be obtained from a single scan, without positioning errors, by finding and storing signals with maximum amplitudes from both coils and correcting for the separation. Enhancement factors can then be calculated as described in R. S. Edwards, S. Dixon and X. Jian: "Depth gauging of defects using low frequency wideband Rayleigh waves", *ibid.*. If liftoff of the receiver
20 9 above the sample 2 can be kept constant during the scan, then only one reference calculation is required at the start of the scan to give the signal amplitude over a section with no defects. Where liftoff is not constant, in-plane and out-of-plane reference values are calculated for each scan point.

25 Referring also Figure 11, a sensor 6_A is shown which comprises a row (along the y-axis) of M generators 8 and a corresponding row (along the y-axis) of N receivers 9, where $M \leq N$ and the generator 8 width * $M \geq$ receiver 9 width * N , and where $N \geq 2$ and preferably $5 \geq N \geq 20$.

30 Figure 12 shows a simplified method of signal processing.

Referring to Figures 1, 2, 3 and 12, the user positions the sensor 9 away from the crack 5, instructs the computer system 13 to acquire reference, and the computer system 13
35 acquires waveforms which serve as a reference (step S15). The user then positions the sensor 6 over the crack in a way that the crack 5 is between the transmitter 8 and

receiver 9, and instructs the computer system 13 to acquire transmission. The computer system 13 acquires waveforms transmitted through the crack (step S16).

5 The user positions the sensor 6, approaching the crack from one chosen side so that a maximum amplitude of enhanced signal is obtained from the first coil 28₁. The user instructs the computer system to acquire maximum amplitude on coil 28₁. The computer system 13 acquires a first waveform from the first coil 28₁ (step S17). The user then moves the sensor 6 to obtain maximum enhanced signal on the second coil 28₂, instructs the computer system to acquire maximum amplitude on coil 28₂. The
10 computer system acquires a waveform from the second coil 28₂ (step S18).

Steps S15, S16, S17 and S18 may be performed in any order.

15 The user then may, optionally, use the system to acquire transmission and enhanced signals approaching the crack from an opposite side, which is equivalent to scanning in reverse direction (step S19).

The computer system 13 calculates transmission, enhancements, enhancement ratio (step S20), obtains crack position (step S21), obtains defect angle (step S22) and defect
20 depth (step S23).

Scanning in forward and reverse directions, acquiring signals and/or processing signals may be carried out by the computer system automatically, i.e. without user
25 intervention.

The sensor may include two rows of receivers 9 with a generator 8 interposed between rear and front receivers 9 and each set of one generator 8 and two receivers 9 arranged in a line (along the x axis).

30 It will be appreciated that various modifications may be made to the embodiments hereinbefore described. Such modifications may involve equivalent and other features which are already known in the design, manufacture and use of EMATs and NDA systems and component parts thereof and which may be used instead of or in addition to features already described herein. Features of one embodiment may be replaced or
35 supplemented by features of another embodiment.

More than one permanent magnet may be used. For example, additional magnets may be placed, along the first axis, either end of the permanent magnet.

Although claims have been formulated in this application to particular combinations of
5 features, it should be understood that the scope of the disclosure of the present
invention also includes any novel features or any novel combination of features
disclosed herein either explicitly or implicitly or any generalization thereof, whether or
not it relates to the same invention as presently claimed in any claim and whether or
not it mitigates any or all of the same technical problems as does the present invention.
10 The applicants hereby give notice that new claims may be formulated to such features
and/or combinations of such features during the prosecution of the present application
or of any further application derived therefrom.

Claims

1. An electromagnetic acoustic transducer based receiver comprising:
a permanent magnet which extends between first and second ends along a first
5 axis and which is magnetised along a second, transverse axis; and
first and second coils wound around the permanent magnet wherein the first and
second coils are wound around the first axis and are spaced apart along the first axis,
wherein the first and second coils are wound close to the first and second ends
respectively such that, when the receiver is presented to a sample, the first and second
10 coils are located adjacent to first and second surface regions of the sample in which
magnetic flux has first and second non-zero components along the first and second axes
respectively.
2. A receiver according to claim 1, comprising at least one additional permanent
15 magnet stacked on top of the permanent magnet along the second axis.
3. A sensor comprising:
a transmitter for generating ultrasonic surface acoustic waves in a sample; and
a receiver according to claim 1 or 2, spaced apart from the transmitter along the
20 sample along the first axis, for measuring surface acoustic waves in the sample.
4. A sensor according to claim 3 wherein the receiver is a first receiver, wherein the
sensor further comprises a second receiver according to claim 1 or 2 and wherein the
transmitter is interposed between the first and second receivers.
25
5. A sensor according to claim 3, comprising at least two rows arranged along a
third axis which is transverse to the first and second axes, each row comprising a
transmitter and a receiver.
- 30 6. A sensor according to claim 4, comprising at least two rows arranged along a
third axis which is transverse to the first and second axes, each row comprising a
transmitter and first and second receivers wherein the transmitter is interposed
between the first and second receivers.
- 35 7. A measurement system comprising:

a pulse generator configured to cause the transmitter to generate the surface acoustic waves in a sample;

a receiver according to claim 1 or 2, wherein the first and second coils generate first and second time varying signals respectively; and

5 a signal processing system configured:

to generate first and second compensated time-varying signals by applying a time shift to at least one of the first and second time-varying signals respectively; and

to calculate an in-plane signal by summing the first and second compensated time-varying signals; and

10 to calculate an out-of-plane signal taking a difference between the first and second compensated time-varying signals.

8. A measurement system according to claim 7, wherein the signal processing system is further configured to display the in-plane signal and/or out-of-plane signal.
15

9. A measurement system according to claim 7 or 8, wherein the signal processing system is further configured to store the in-plane signal and/or out-of-plane signal.

10. A method of processing surface acoustic wave signals comprising:
20 receiving first and second time varying signals;
generating first and second compensated time-varying signals by applying a time shift to at least one of the first and second time-varying signals respectively;
calculating an in-plane signal by summing the first and second compensated time-varying signals; and
25 calculating an out-of-plane signal taking a difference between the first and second compensated time-varying signals

11. A computer program which, when executed by a computer, causes the computer to perform a method according to claim 10.
30

12. A computer program product comprising a computer-readable medium storing a computer program according to claim 11.

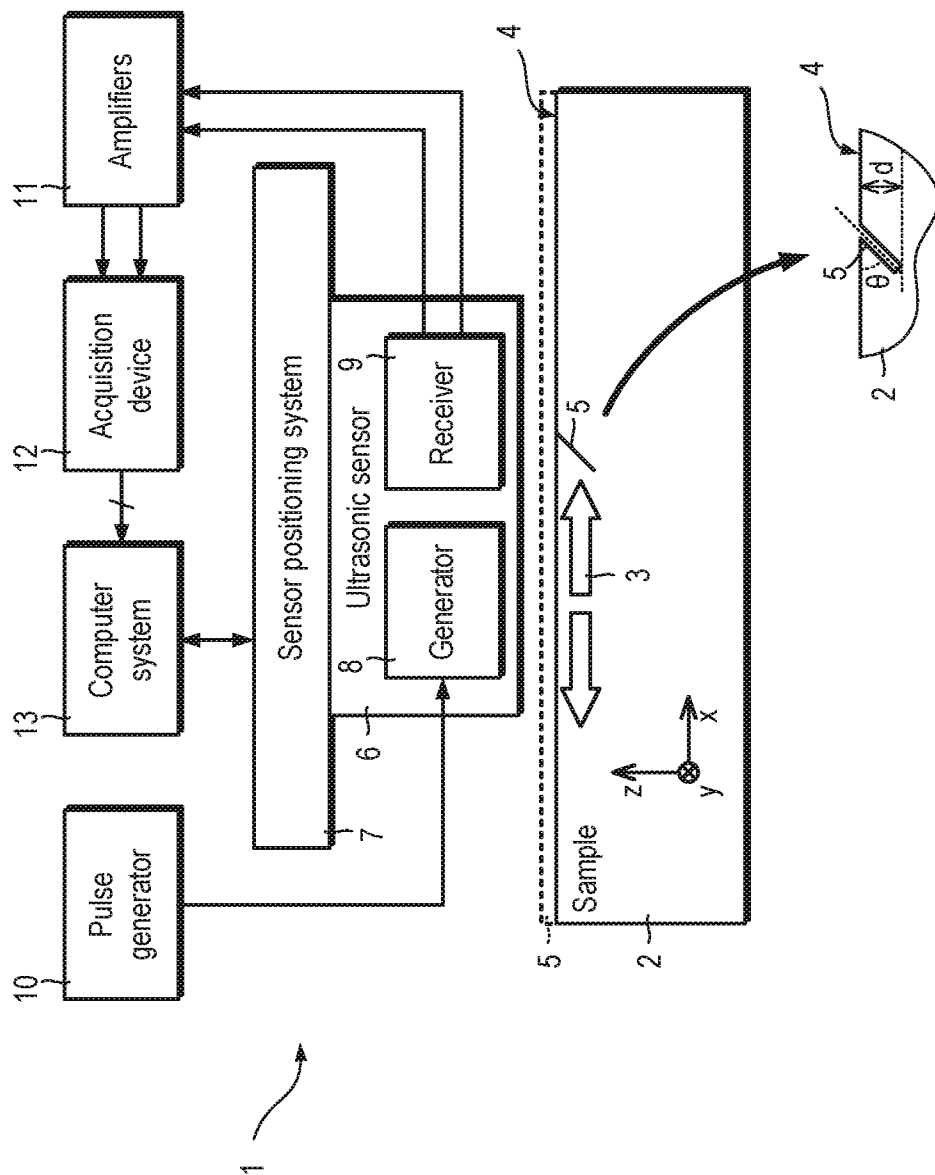


Fig. 1

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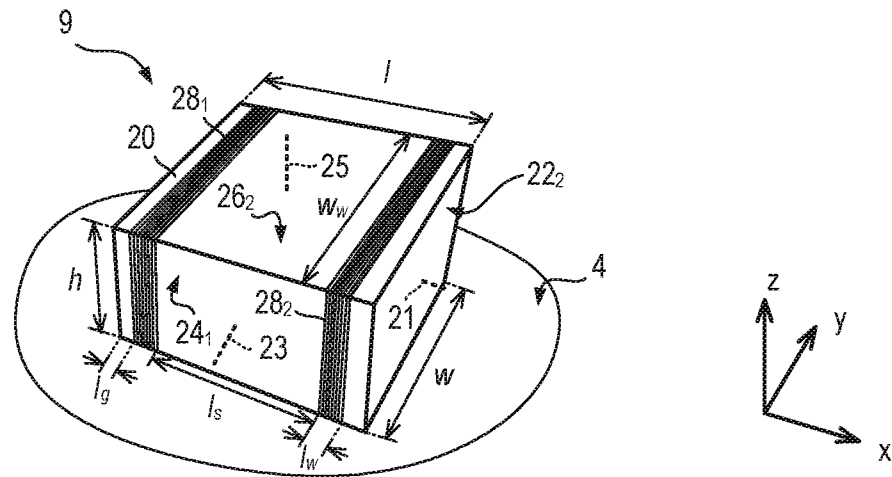


Fig. 2

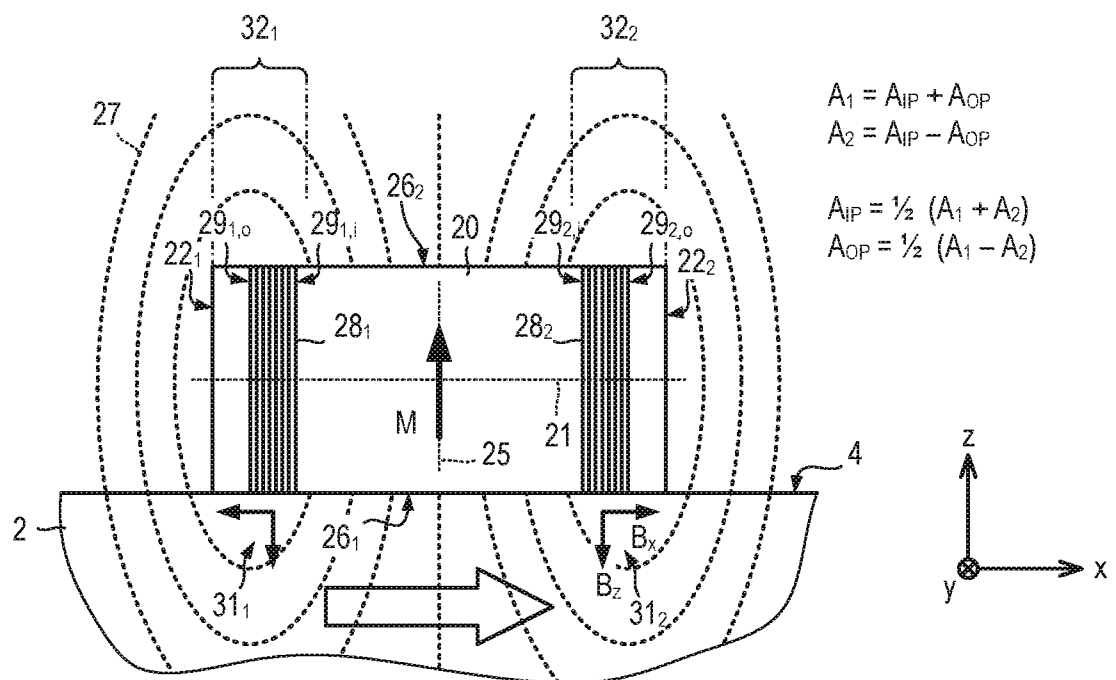


Fig. 3

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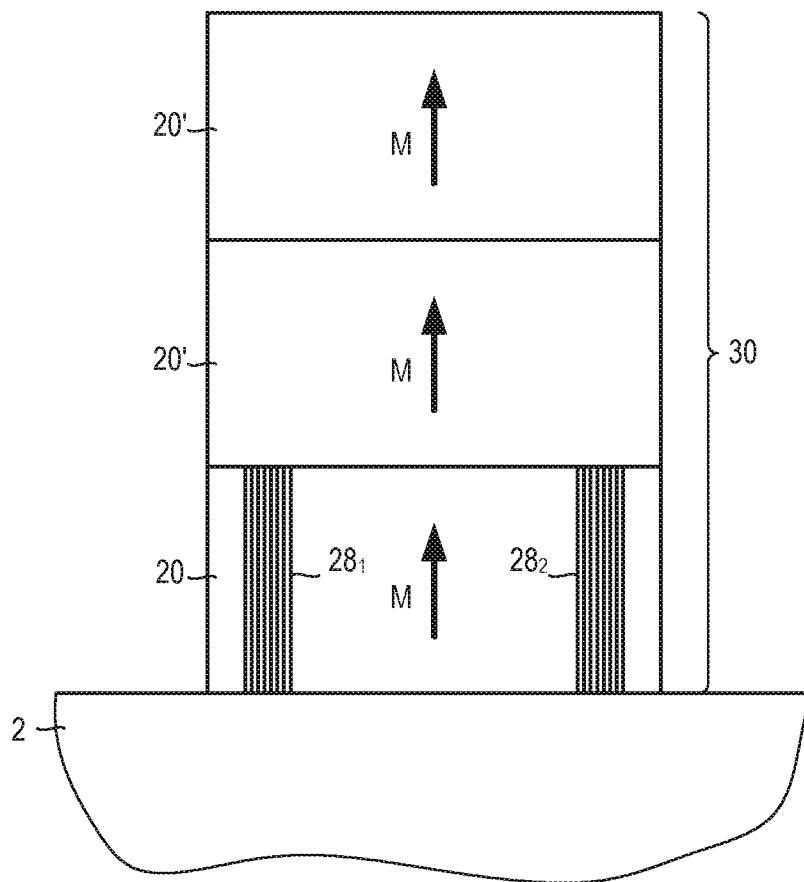


Fig. 4

13

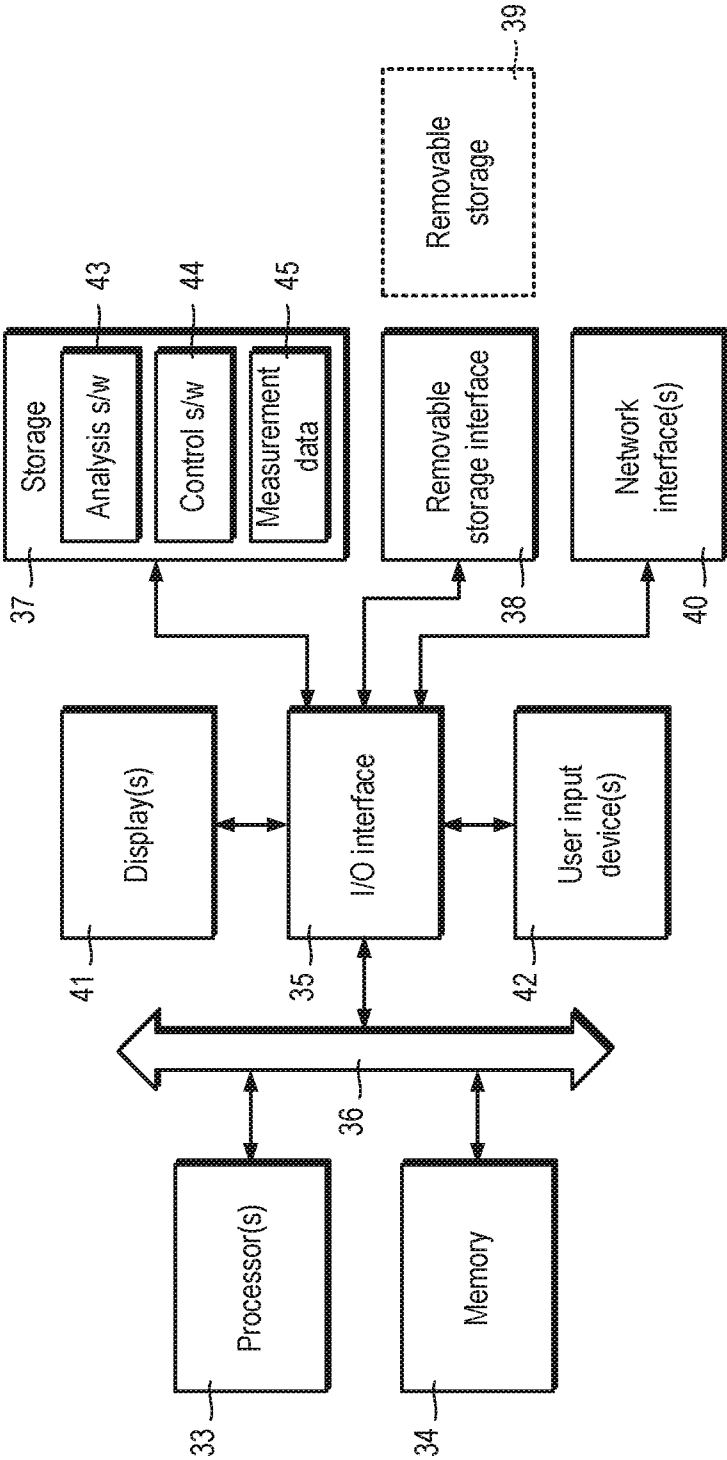


Fig. 5

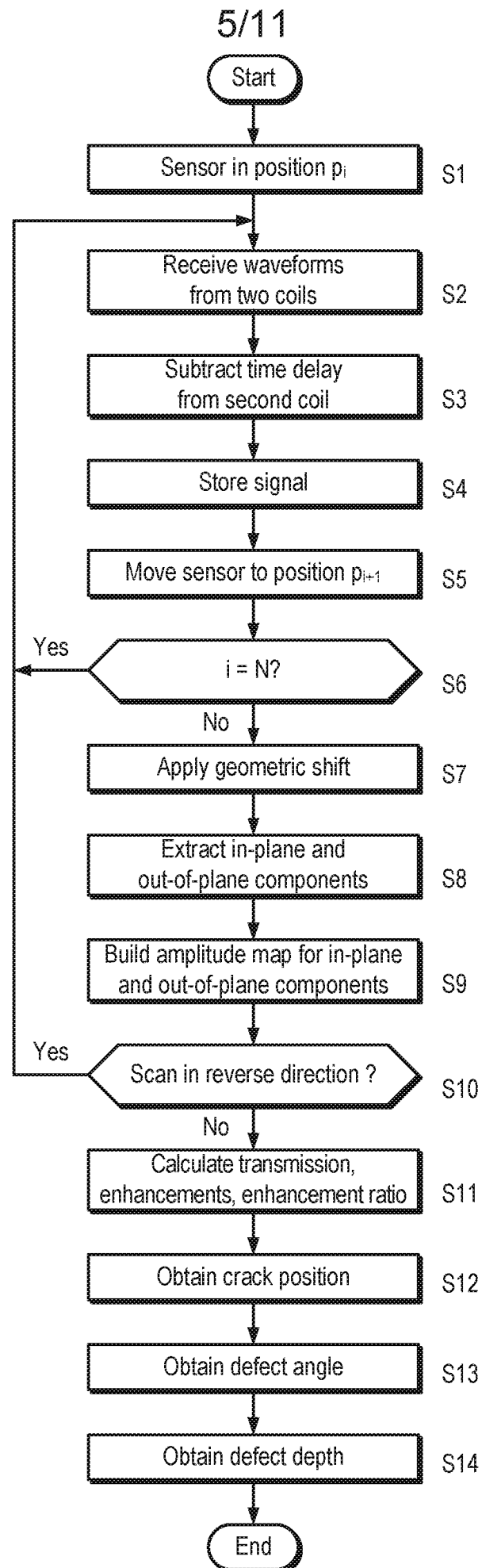


Fig. 6

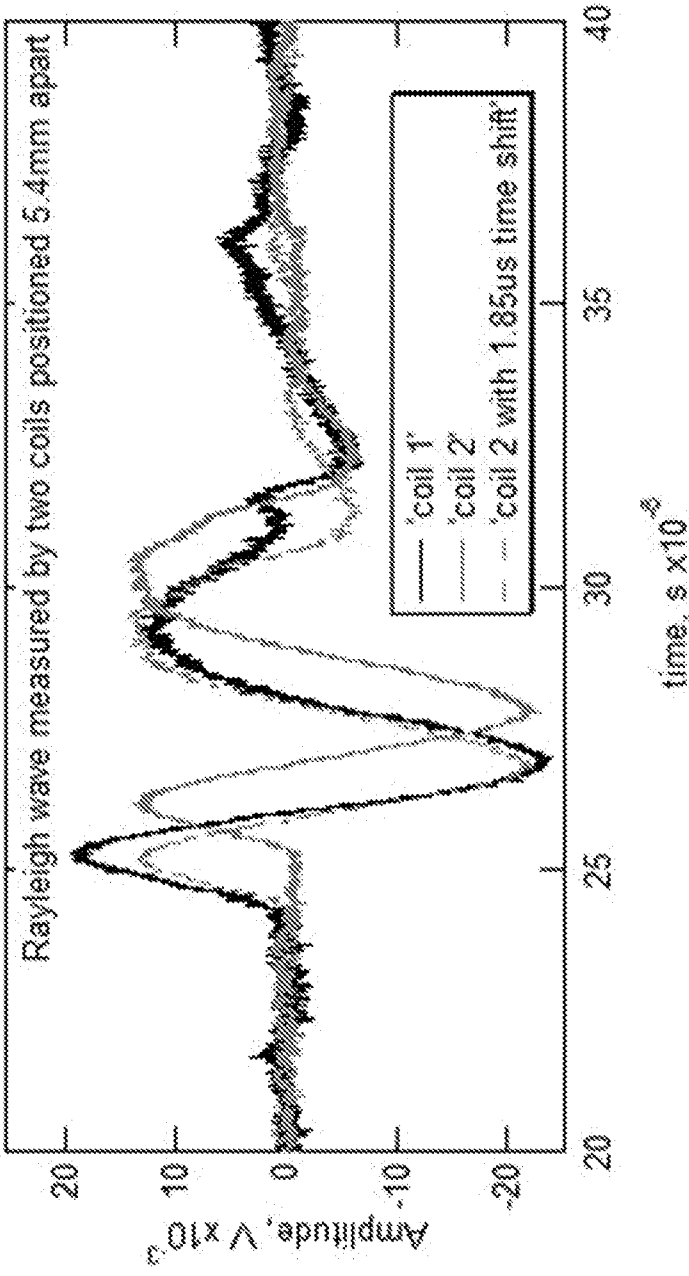


Fig. 7

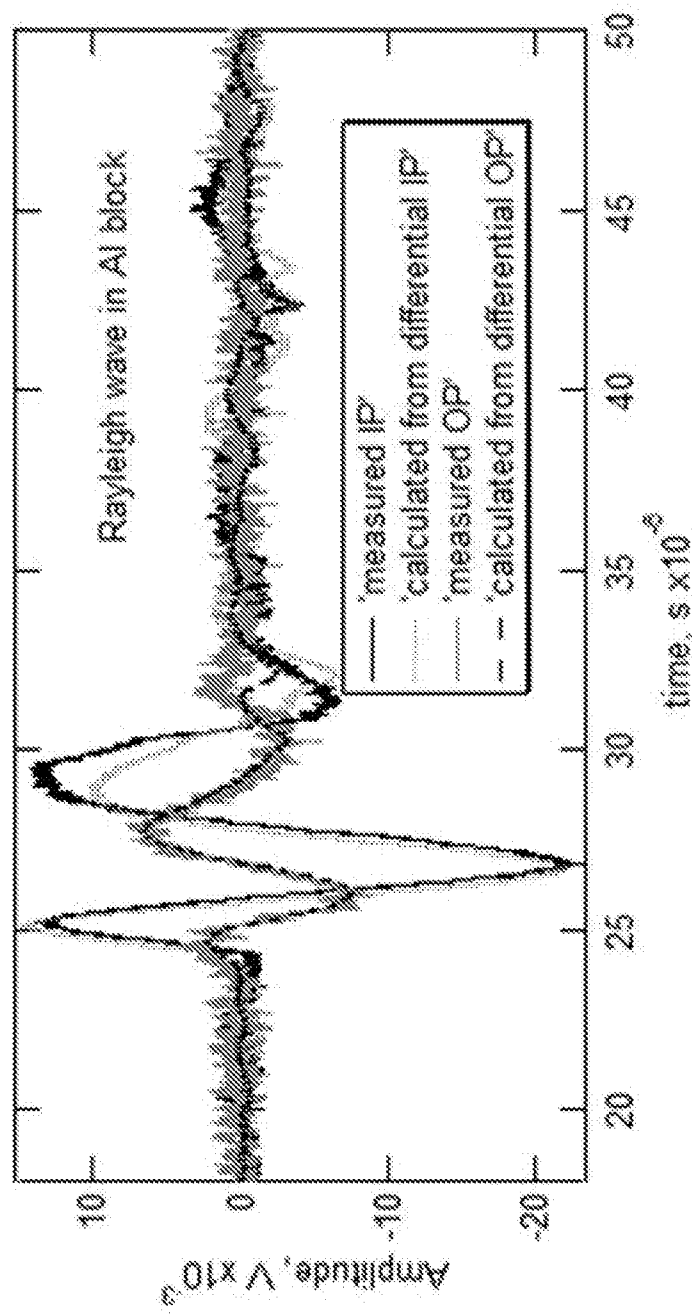


Fig. 8

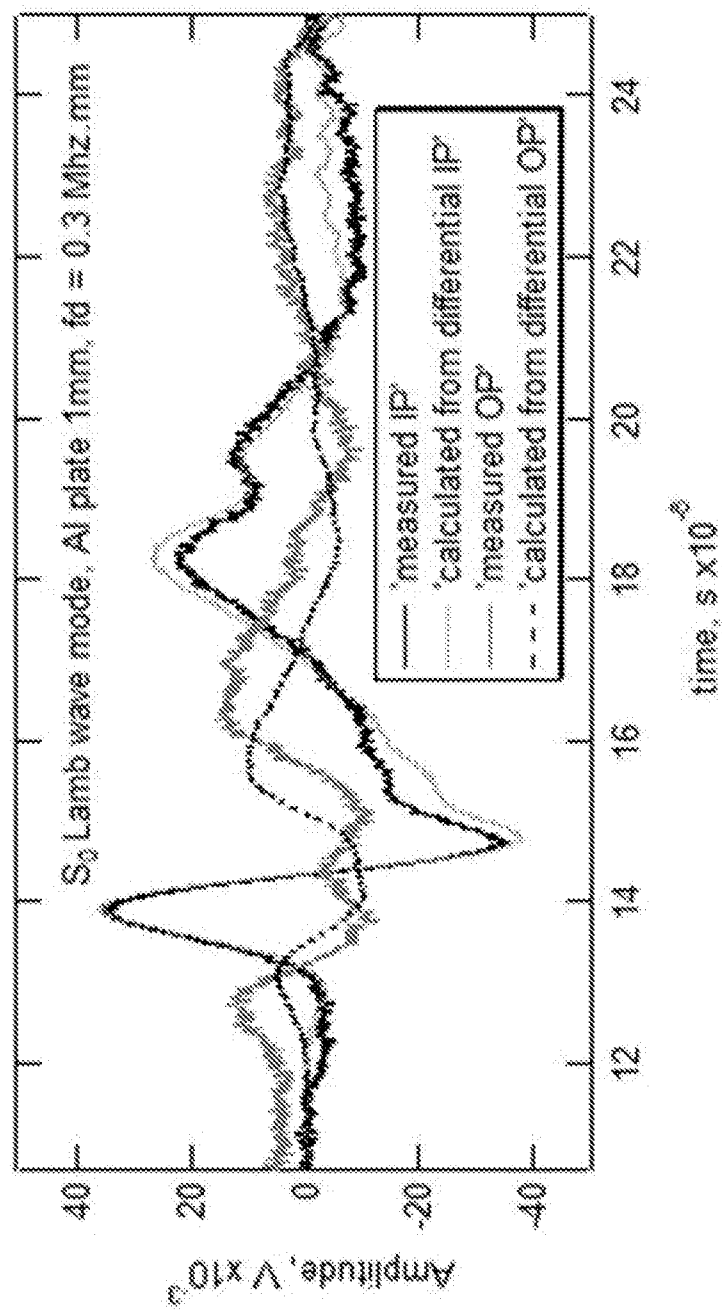


Fig. 9

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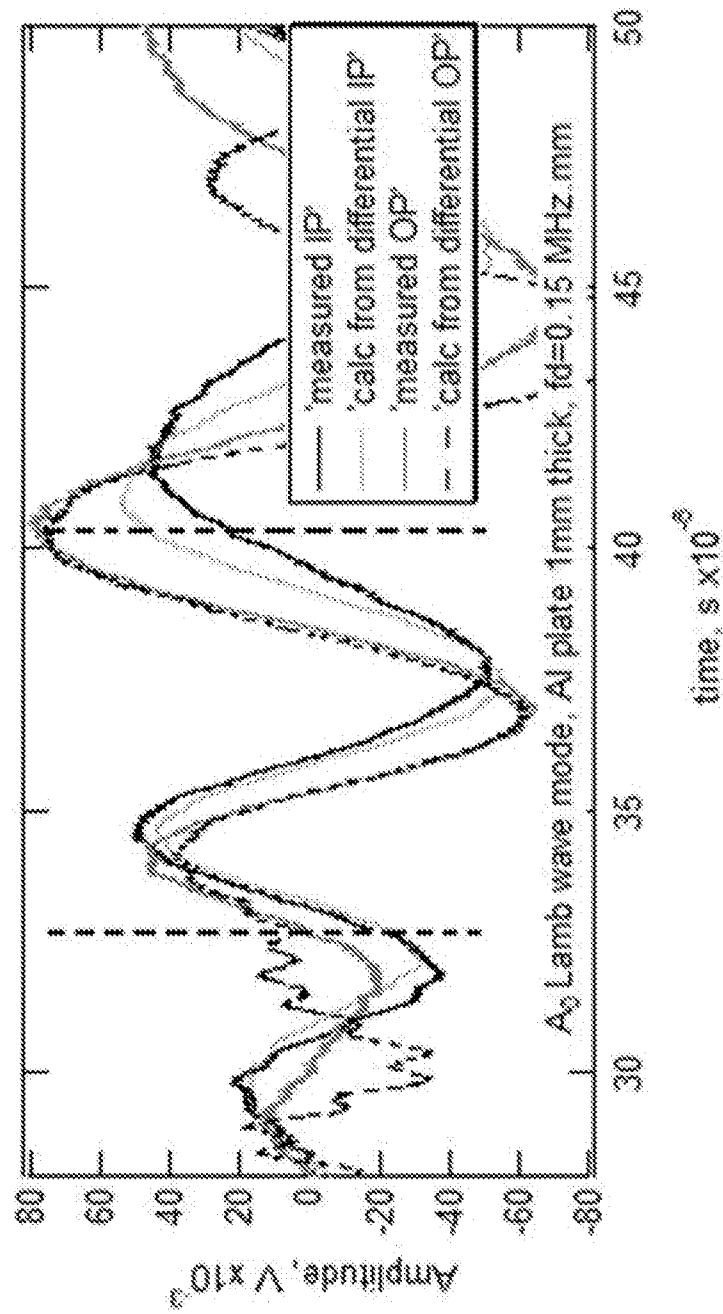


Fig. 10

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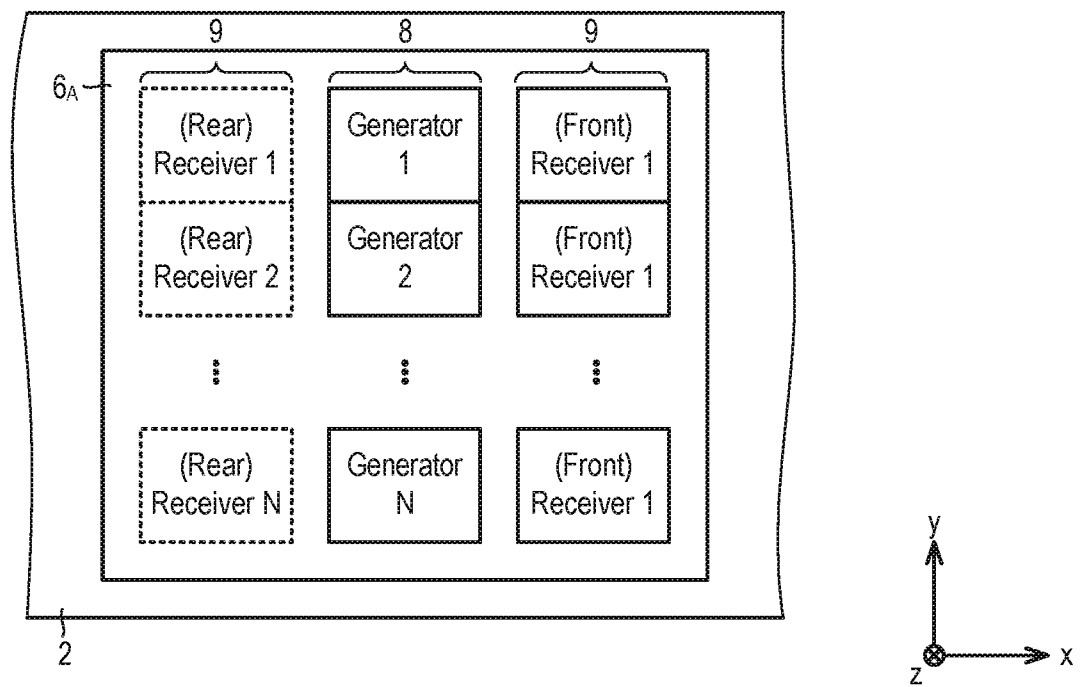


Fig. 11

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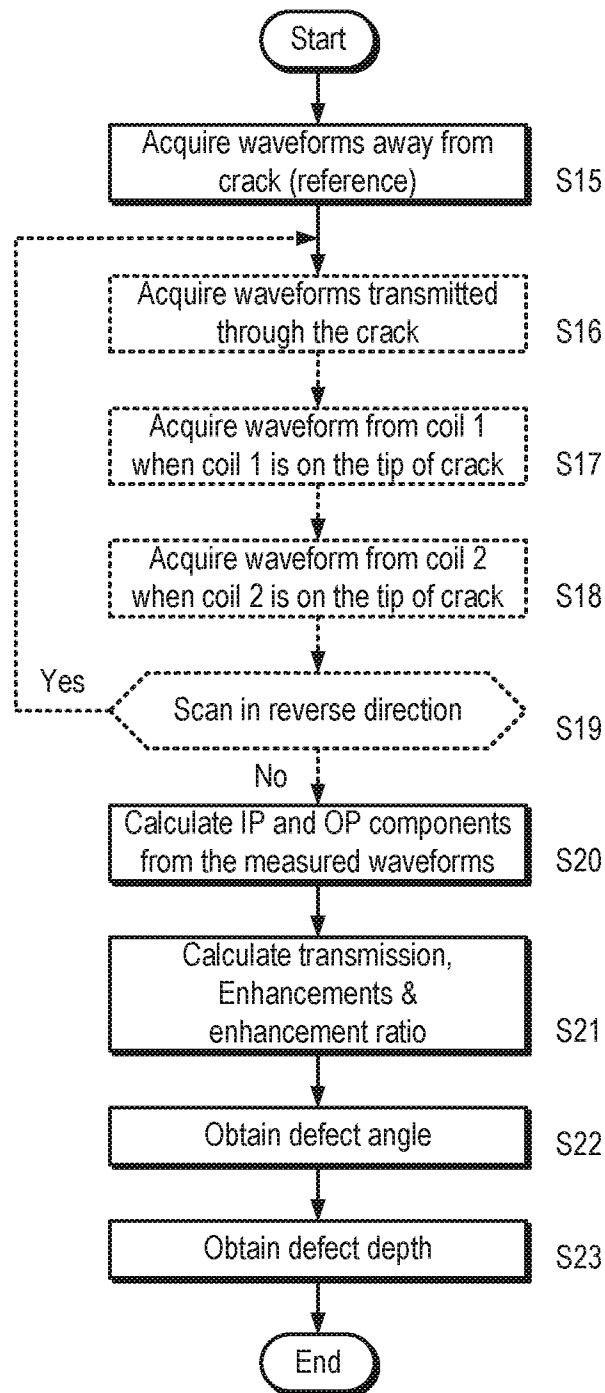


Fig. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/052869

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01N29/04 B06B1/08 G01N27/72 G01N27/87 G01N29/24
G01N29/44 H01F7/02

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N B06B H01F

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

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

EPO-Internal, WPI Data, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 218 924 A (FORTUNKO CHRISTOPHER M [US] ET AL) 26 August 1980 (1980-08-26) abstract; figure 1	1-9
A	GB 2 113 392 A (VNII RAZRABOTKE NERAZRUSCHA) 3 August 1983 (1983-08-03) page 1, lines 6-12, 79-92; figure 1	1-9
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Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

27 November 2017

Date of mailing of the international search report

01/12/2017

Name and mailing address of the ISA/

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Authorized officer

Filipas, Alin

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2017/052869

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JIAN X ET AL: "Electromagnetic acoustic transducers for in- and out-of plane ultrasonic wave detection", SENSORS AND ACTUATORS A: PHYSICAL, ELSEVIER BV, NL, vol. 148, no. 1, 4 November 2008 (2008-11-04), pages 51-56, XP025535263, ISSN: 0924-4247, DOI: 10.1016/J.SNA.2008.07.004 [retrieved on 2008-07-23] page 51, left-hand column page 53, last paragraph; figure 5 -----	1-12

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2017/052869

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 4218924	A	26-08-1980	NONE	

GB 2113392	A	03-08-1983	DE 3301118 A1	28-07-1983
			FR 2520120 A1	22-07-1983
			GB 2113392 A	03-08-1983
