(56) **References Cited**

OTHER PUBLICATIONS

Thomas et al., "Corrosion Damage Detection with Piezoelectric Wafer Active Sensors", SPIE's 11th Annual International Symposium on Smart Structures and Materials and 9th Annual International Symposium on NDE for Health Monitoring and Diagnostics, Mar. 2004, San Diego CA, paper #5394-2, pp. 1-13.

Sohn et al., "Statistical Damage Classification under Changing environmental and Operational Conditions", Journal of Intelligent Materials Systems and Structures, 1992, pp. 1-17.

Oh et al., "Damage diagnosis under environmental and operational variations using unsupervised support vector machine", Elsevier, Journal of Sound and Vibration, 2009, pp. 1-16.

Park et al., "Time Reversal Active Sensing for Health Monitoring of a Composite Plate", Journal of Sound and Vibration, 2004, pp. 1-33.

Yeum et al., "Lamb wave mode decomposition using concentric ring and circular piezoelectric transducers", Wave Motion (2011), pp. 1-13.

Kim et al., "Instantaneous reference-free crack detection based on polarization characteristics of piezoelectric materials", Smart Materials and Structures, 2007, pp. 2375-2387.

Wooh et al., "Synthetic Phase Tuning of Guided Waves", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 48 No. 1, Jan. 2001, pp. 209-223.

Santoni et al., "Lamb Wave-Mode Tuning of Piezoelectric Wafer Active Sensors for Structural Health Monitoring", Transactions of the ASME, vol. 129, Dec. 2007, pp. 752-763.

U.S. Appl. No. 13/083,957, filed Apr. 11, 2011, Sohn et al.

Office Action, dated Aug. 22, 2012, regarding USPTO U.S. Appl. No. 13/083,957, 13 pages.

Notice of Allowance, dated May 30, 2013, regarding USPTO U.S. Appl. No. 13/083,957, 9 pages.

Final Office Action, dated Feb. 6, 2013, regarding USPTO U.S. Appl. No. 13/083,957, 10 pages.

* cited by examiner

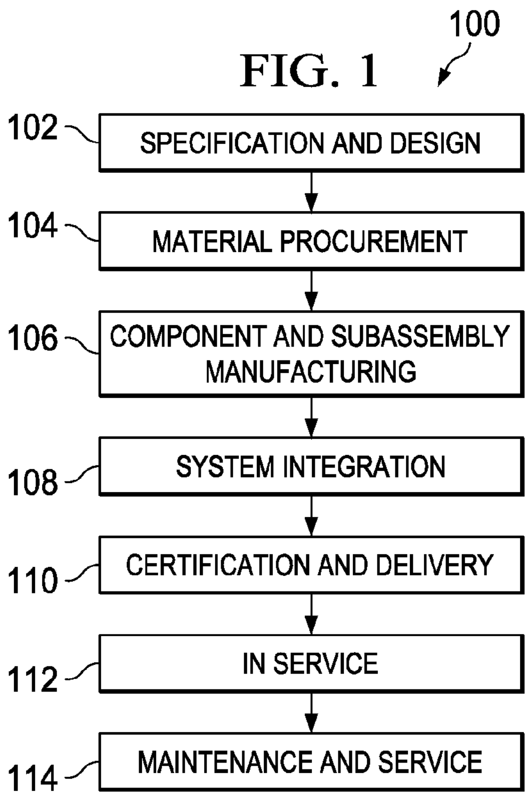

100
102
SPECIFICATION AND DESIGN
104
MATERIAL PROCUREMENT
106
COMPONENT AND SUBASSEMBLY MANUFACTURING
108
SYSTEM INTEGRATION
110
CERTIFICATION AND DELIVERY
112
IN SERVICE
114
MAINTENANCE AND SERVICE

FIG. 1

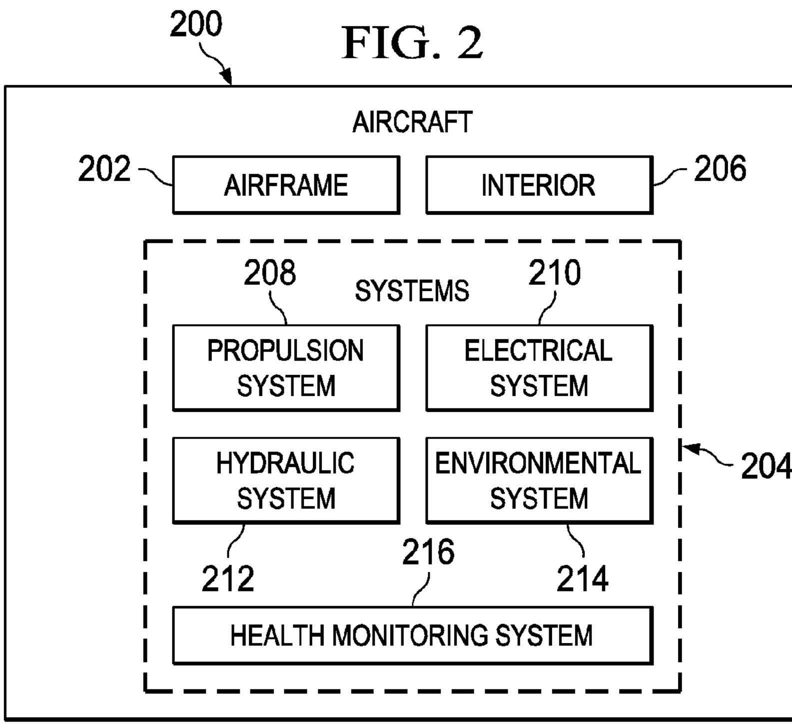

200
AIRCRAFT
202
AIRFRAME
INTERIOR
206
SYSTEMS
208
210
PROPULSION SYSTEM
ELECTRICAL SYSTEM
HYDRAULIC SYSTEM
ENVIRONMENTAL SYSTEM
204
212
216
214
HEALTH MONITORING SYSTEM

FIG. 2

FIG. 3

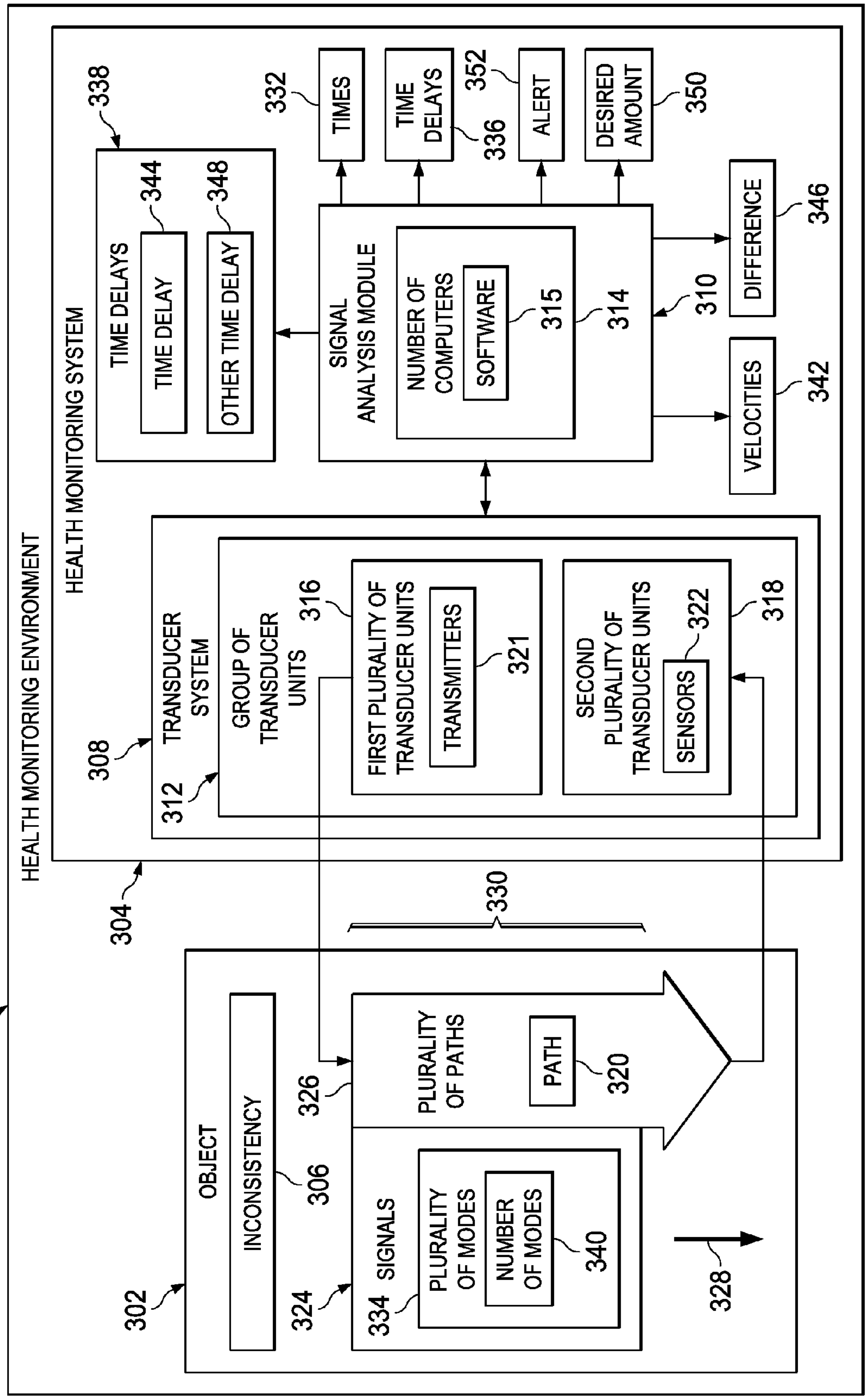
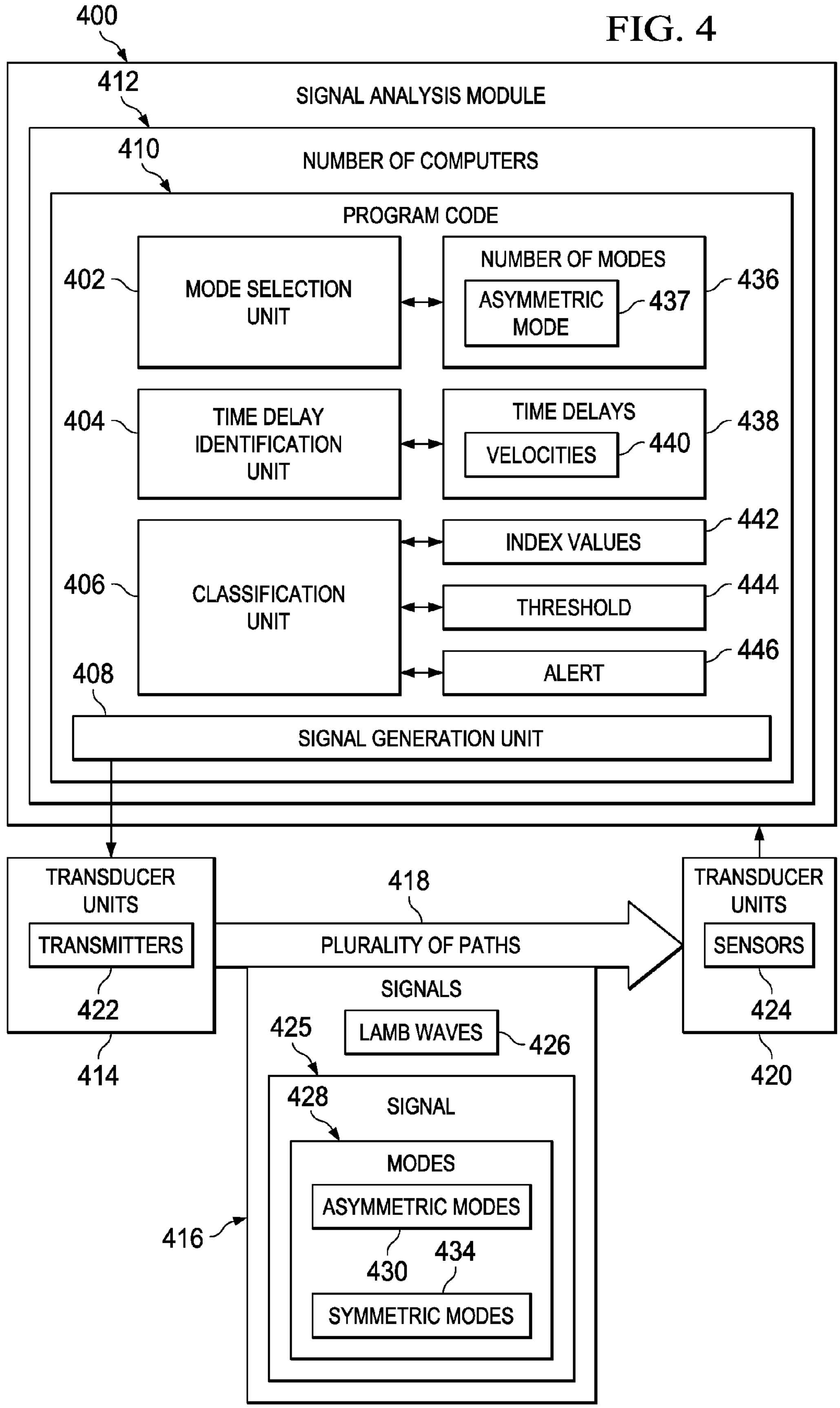

300
HEALTH MONITORING ENVIRONMENT
304
HEALTH MONITORING SYSTEM
338
TIME DELAYS
TIME DELAY
344
OTHER TIME DELAY
348
332
TIMES
TIME DELAYS
336
352
ALERT
DESIRED AMOUNT
350
SIGNAL ANALYSIS MODULE
NUMBER OF COMPUTERS
SOFTWARE
315
314
310
DIFFERENCE
346
VELOCITIES
342
308
TRANSDUCER SYSTEM
312
GROUP OF TRANSDUCER UNITS
316
FIRST PLURALITY OF TRANSDUCER UNITS
TRANSMITTERS
321
SECOND PLURALITY OF TRANSDUCER UNITS
SENSORS
322
318
330
302
OBJECT
INCONSISTENCY
306
326
PLURALITY OF PATHS
PATH
320
324
SIGNALS
334
PLURALITY OF MODES
NUMBER OF MODES
340
328

FIG. 4



400
412
SIGNAL ANALYSIS MODULE
410
NUMBER OF COMPUTERS
PROGRAM CODE
402
MODE SELECTION UNIT
NUMBER OF MODES
ASYMMETRIC MODE
437
436
404
TIME DELAY IDENTIFICATION UNIT
TIME DELAYS
VELOCITIES
440
438
442
INDEX VALUES
406
CLASSIFICATION UNIT
444
THRESHOLD
446
ALERT
408
SIGNAL GENERATION UNIT
TRANSDUCER UNITS
TRANSMITTERS
422
414
418
PLURALITY OF PATHS
TRANSDUCER UNITS
SENSORS
424
420
SIGNALS
LAMB WAVES
425
426
428
SIGNAL
MODES
ASYMMETRIC MODES
430
434
SYMMETRIC MODES
416

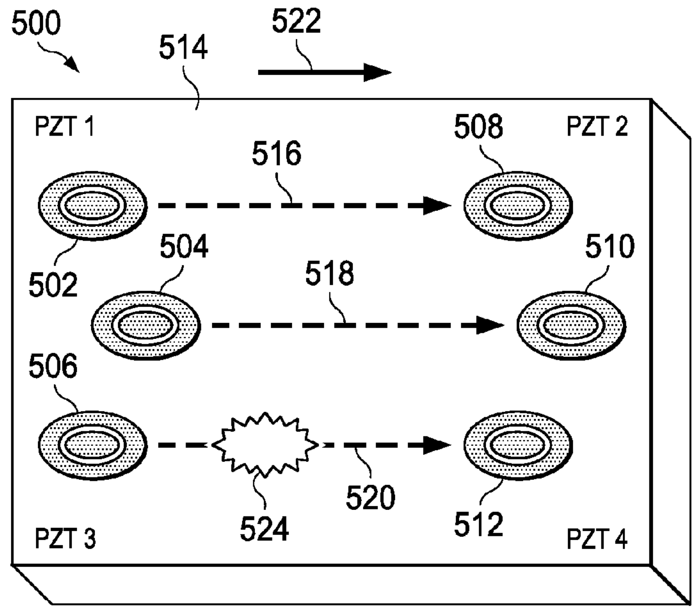

500
514
522
PZT 1
508
PZT 2
516
504
510
502
518
506
524
520
512
PZT 3
PZT 4

FIG. 5

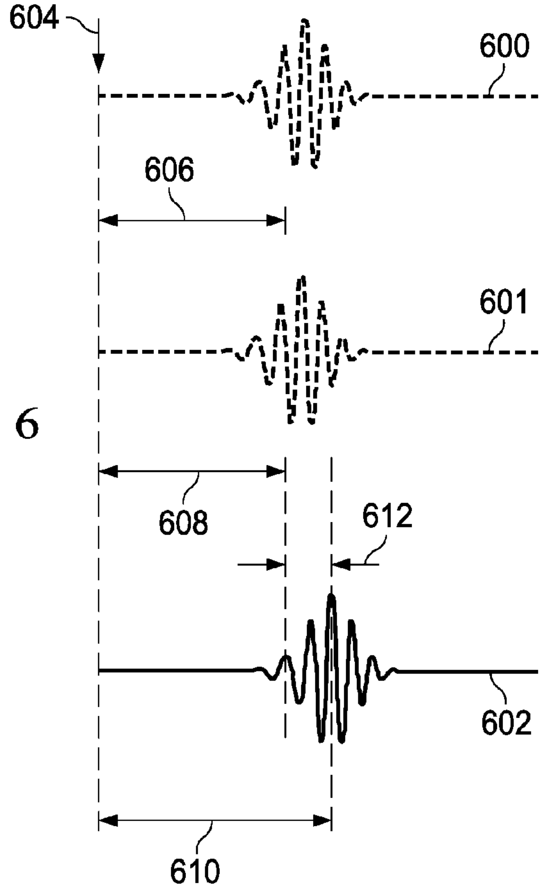
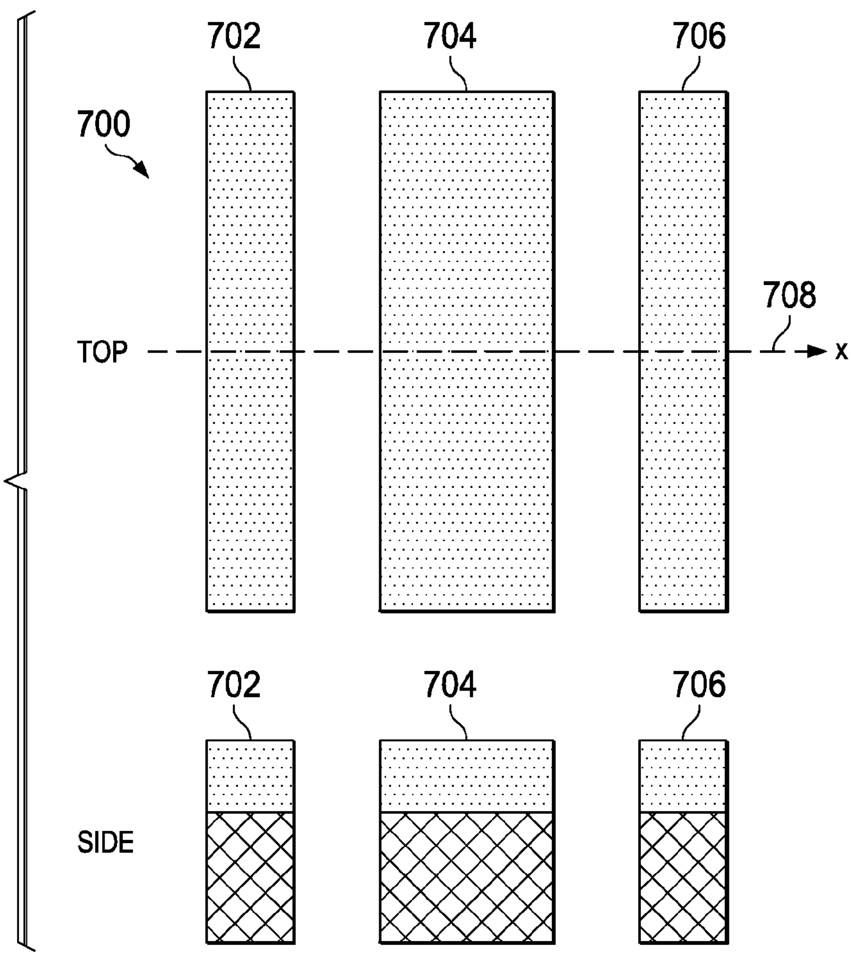

604
600
606
601
608
612
602
610

FIG. 6

FIG. 7



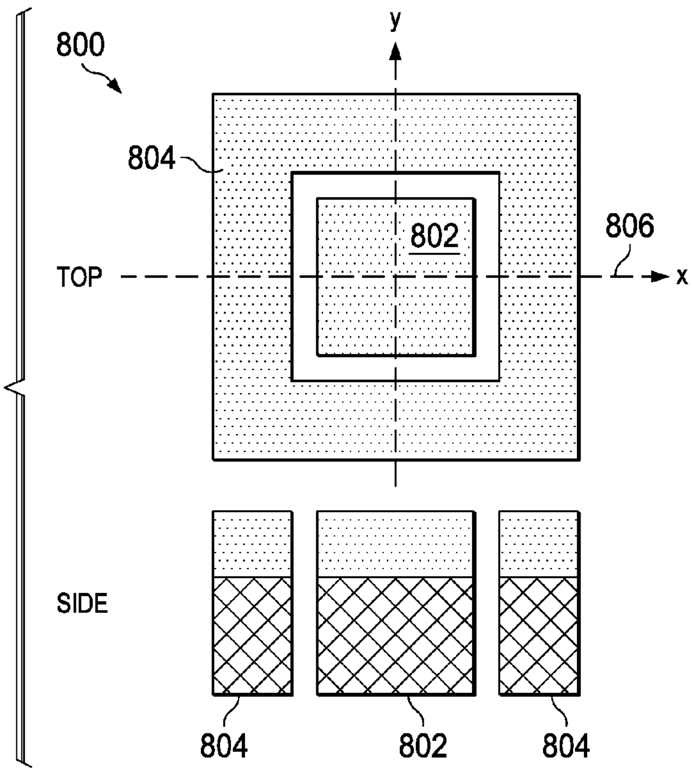

800
804
802
806
y
x
TOP
SIDE
804
802
804

FIG. 8

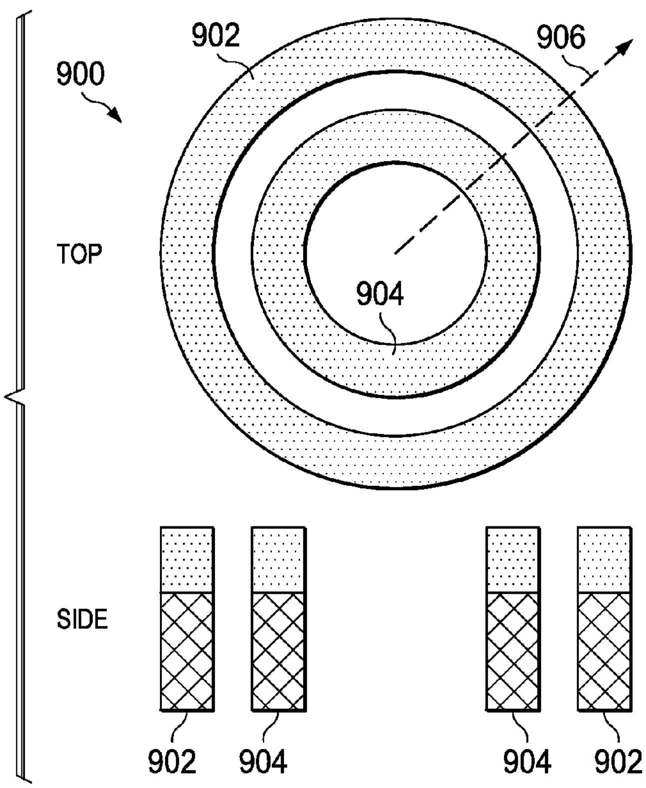

900
902
906
904
TOP
SIDE
902
904
904
902

FIG. 9

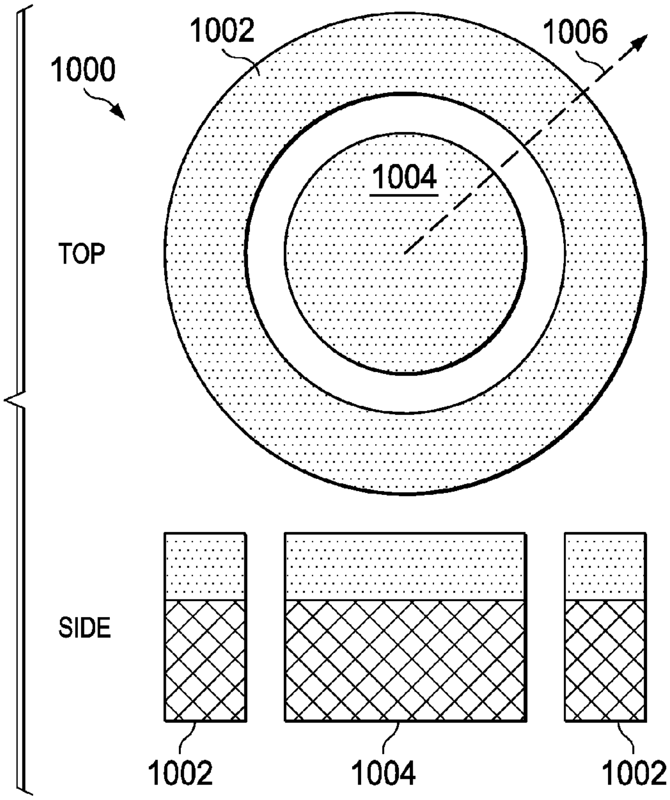

1000
1002
1006
1004
TOP
SIDE
1002
1004
1002

FIG. 10

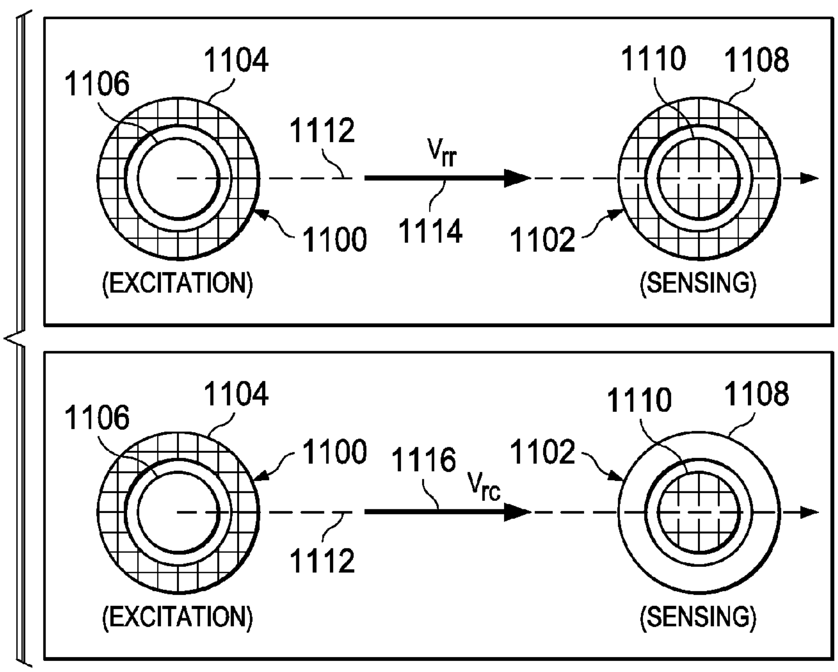

1106
1104
1112
V_{rr}
1110
1108
1100
1114
1102
(EXCITATION)
(SENSING)
1106
1104
1100
1116
V_{rc}
1102
1110
1108
1112
(EXCITATION)
(SENSING)

FIG. 11

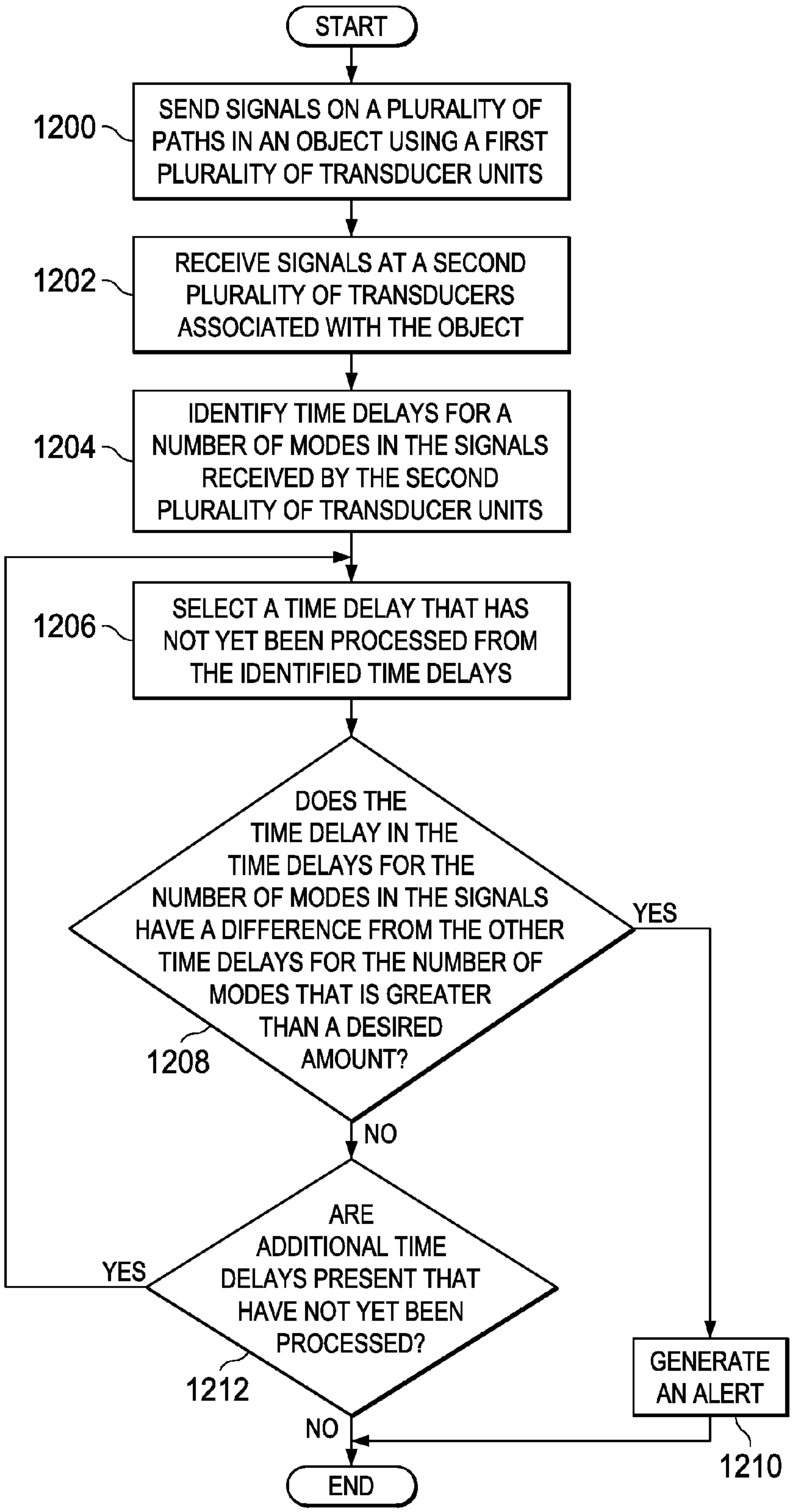
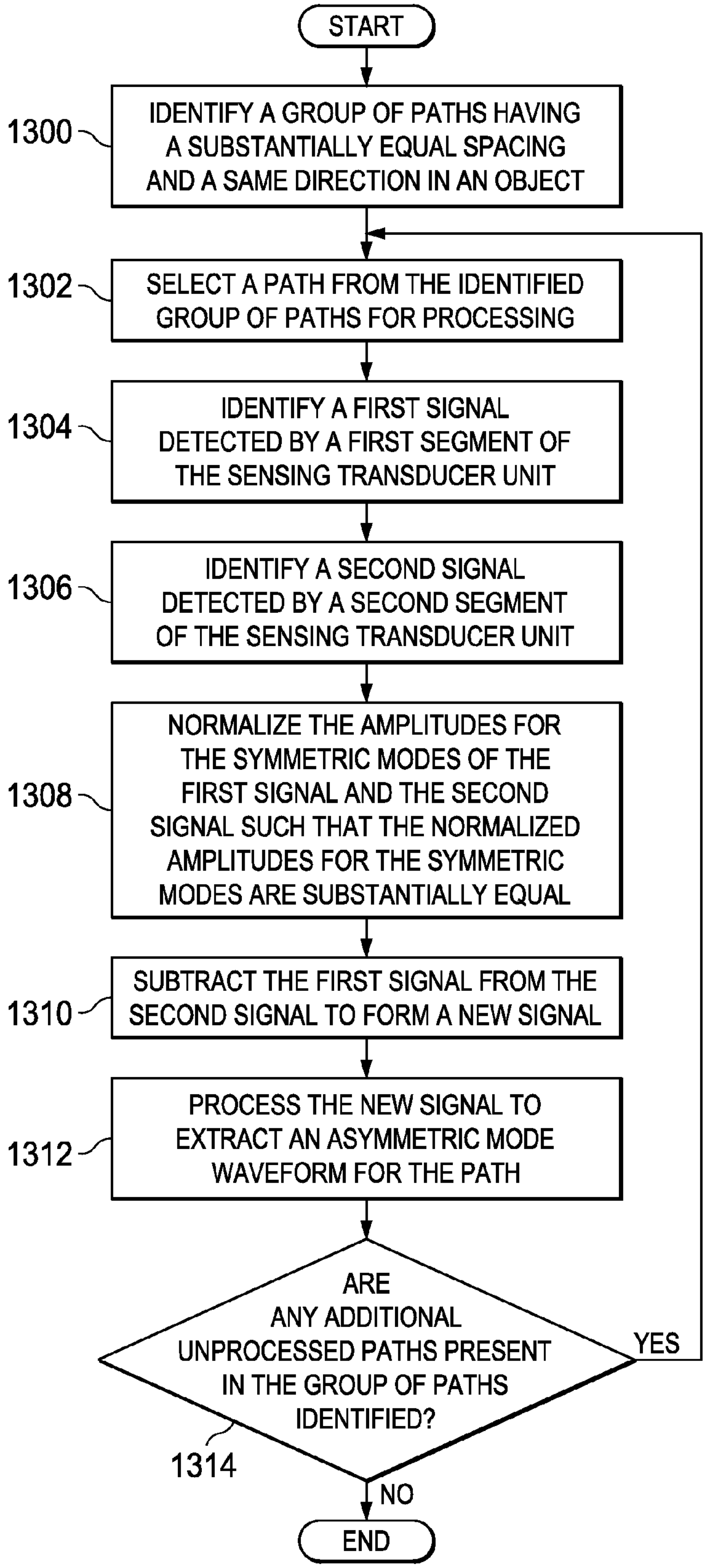

START
1200
SEND SIGNALS ON A PLURALITY OF PATHS IN AN OBJECT USING A FIRST PLURALITY OF TRANSDUCER UNITS
1202
RECEIVE SIGNALS AT A SECOND PLURALITY OF TRANSDUCERS ASSOCIATED WITH THE OBJECT
1204
IDENTIFY TIME DELAYS FOR A NUMBER OF MODES IN THE SIGNALS RECEIVED BY THE SECOND PLURALITY OF TRANSDUCER UNITS
1206
SELECT A TIME DELAY THAT HAS NOT YET BEEN PROCESSED FROM THE IDENTIFIED TIME DELAYS
DOES THE TIME DELAY IN THE TIME DELAYS FOR THE NUMBER OF MODES IN THE SIGNALS HAVE A DIFFERENCE FROM THE OTHER TIME DELAYS FOR THE NUMBER OF MODES THAT IS GREATER THAN A DESIRED AMOUNT?
1208
YES
NO
ARE ADDITIONAL TIME DELAYS PRESENT THAT HAVE NOT YET BEEN PROCESSED?
1212
YES
NO
GENERATE AN ALERT
1210
END

FIG. 12



START
1300
IDENTIFY A GROUP OF PATHS HAVING A SUBSTANTIALLY EQUAL SPACING AND A SAME DIRECTION IN AN OBJECT
1302
SELECT A PATH FROM THE IDENTIFIED GROUP OF PATHS FOR PROCESSING
1304
IDENTIFY A FIRST SIGNAL DETECTED BY A FIRST SEGMENT OF THE SENSING TRANSDUCER UNIT
1306
IDENTIFY A SECOND SIGNAL DETECTED BY A SECOND SEGMENT OF THE SENSING TRANSDUCER UNIT
1308
NORMALIZE THE AMPLITUDES FOR THE SYMMETRIC MODES OF THE FIRST SIGNAL AND THE SECOND SIGNAL SUCH THAT THE NORMALIZED AMPLITUDES FOR THE SYMMETRIC MODES ARE SUBSTANTIALLY EQUAL
1310
SUBTRACT THE FIRST SIGNAL FROM THE SECOND SIGNAL TO FORM A NEW SIGNAL
1312
PROCESS THE NEW SIGNAL TO EXTRACT AN ASYMMETRIC MODE WAVEFORM FOR THE PATH
ARE ANY ADDITIONAL UNPROCESSED PATHS PRESENT IN THE GROUP OF PATHS IDENTIFIED?
1314
YES
NO
END

FIG. 13

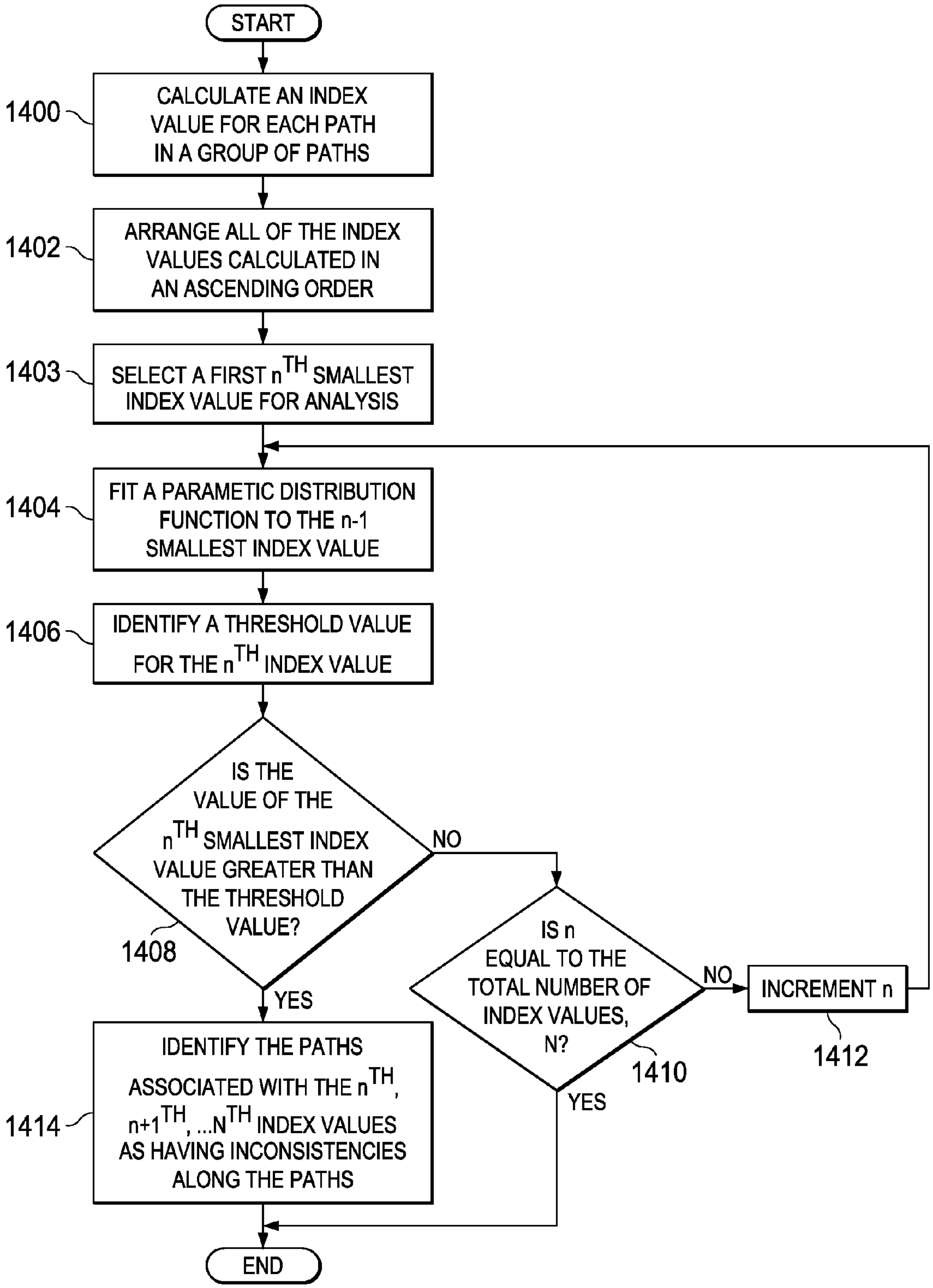

START
1400
CALCULATE AN INDEX VALUE FOR EACH PATH IN A GROUP OF PATHS
1402
ARRANGE ALL OF THE INDEX VALUES CALCULATED IN AN ASCENDING ORDER
1403
SELECT A FIRST nTH SMALLEST INDEX VALUE FOR ANALYSIS
1404
FIT A PARAMETRIC DISTRIBUTION FUNCTION TO THE n-1 SMALLEST INDEX VALUE
1406
IDENTIFY A THRESHOLD VALUE FOR THE nTH INDEX VALUE
IS THE VALUE OF THE nTH SMALLEST INDEX VALUE GREATER THAN THE THRESHOLD VALUE?
1408
NO
YES
IS n EQUAL TO THE TOTAL NUMBER OF INDEX VALUES, N?
1410
NO
YES
INCREMENT n
1412
1414
IDENTIFY THE PATHS ASSOCIATED WITH THE nTH, n+1TH, ...NTH INDEX VALUES AS HAVING INCONSISTENCIES ALONG THE PATHS
END

FIG. 14

FIG. 15

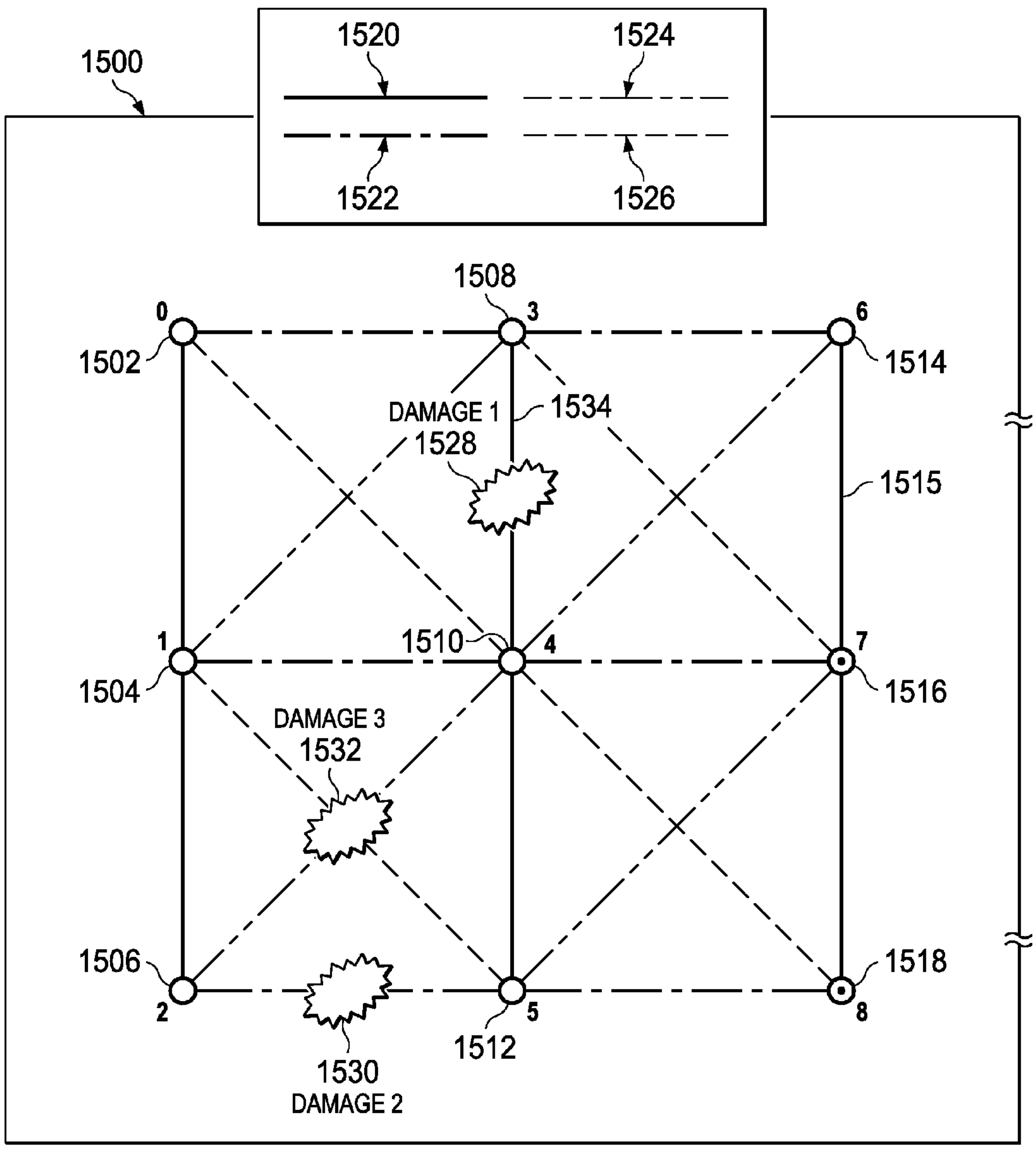

1500
1520
1524
1522
1526
1508
0
3
6
1502
1514
DAMAGE 1
1528
1534
1515
1
1510
4
7
1504
1516
DAMAGE 3
1532
1506
1518
2
5
8
1512
1530
DAMAGE 2

FIG. 16

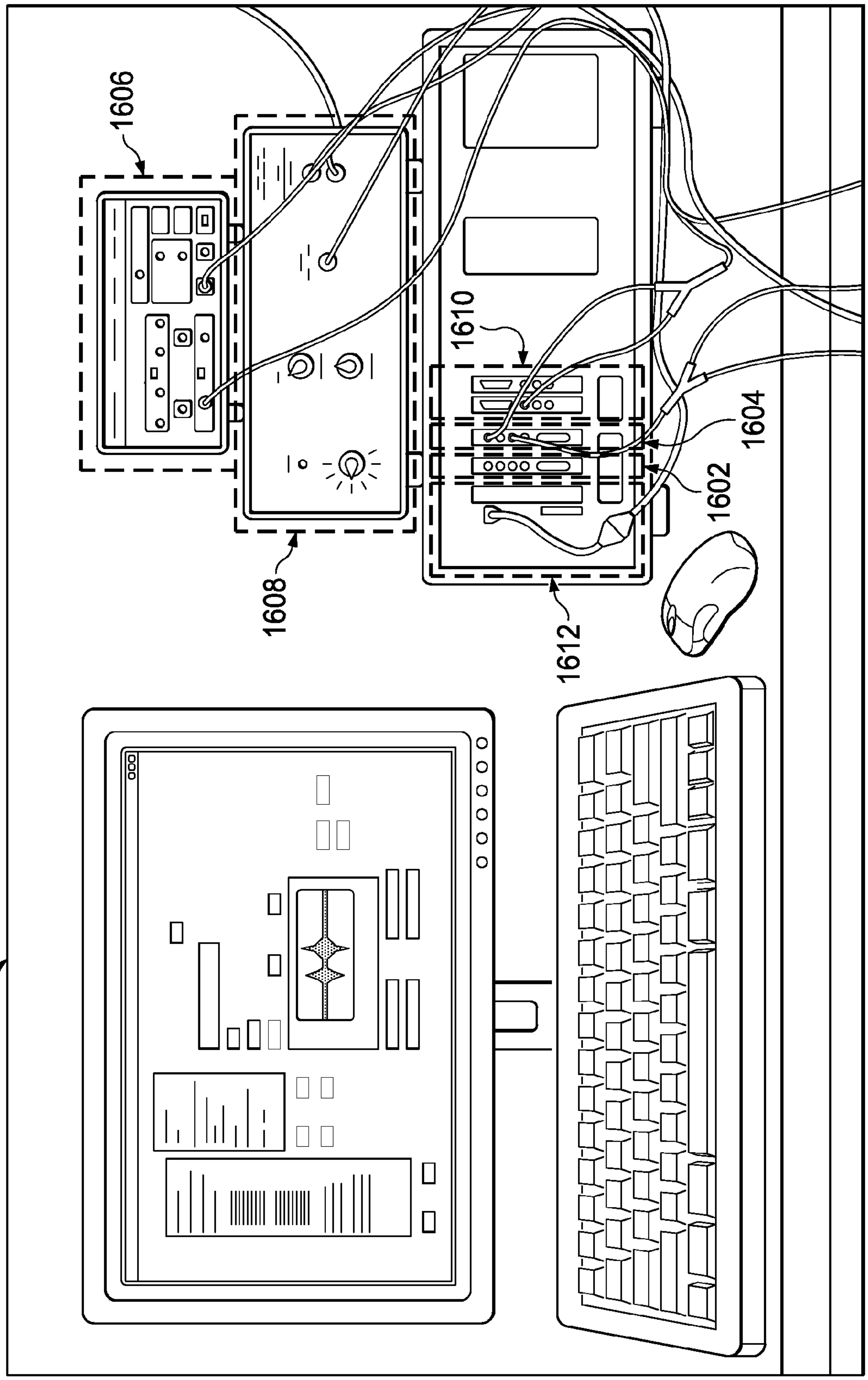


FIG. 17

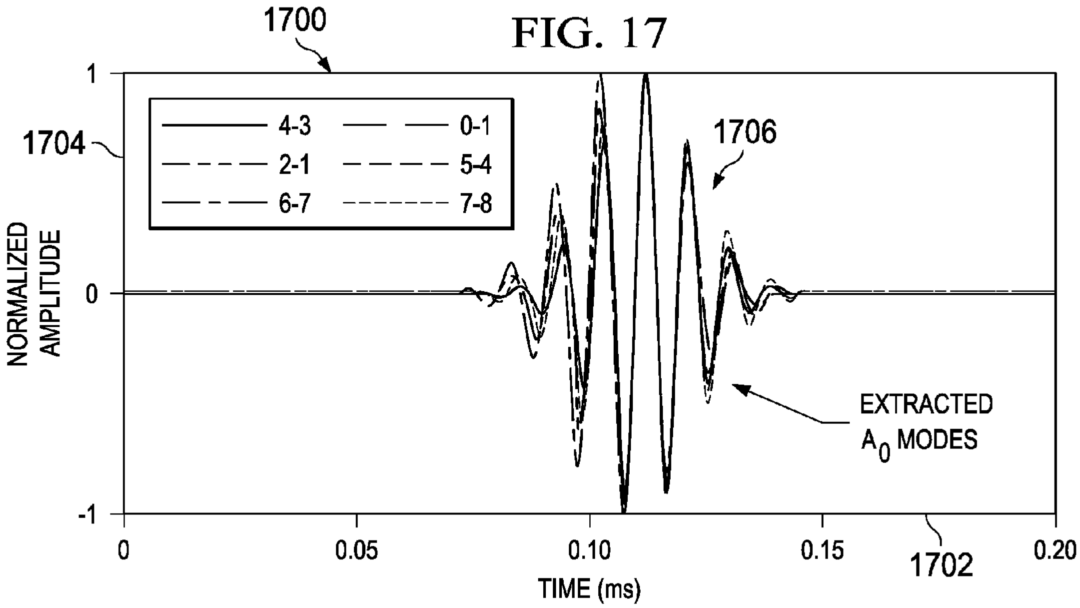

1700
1704
1706
4-3
0-1
2-1
5-4
6-7
7-8
NORMALIZED AMPLITUDE
1
0
-1
0
0.05
0.10
0.15
0.20
TIME (ms)
1702
EXTRACTED A_0 MODES

FIG. 18

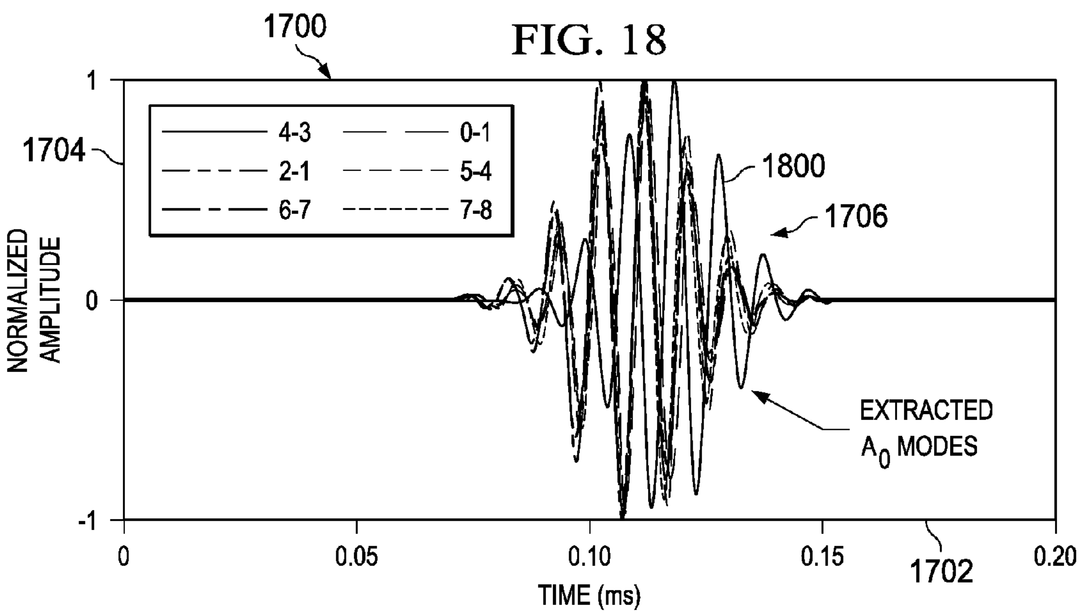
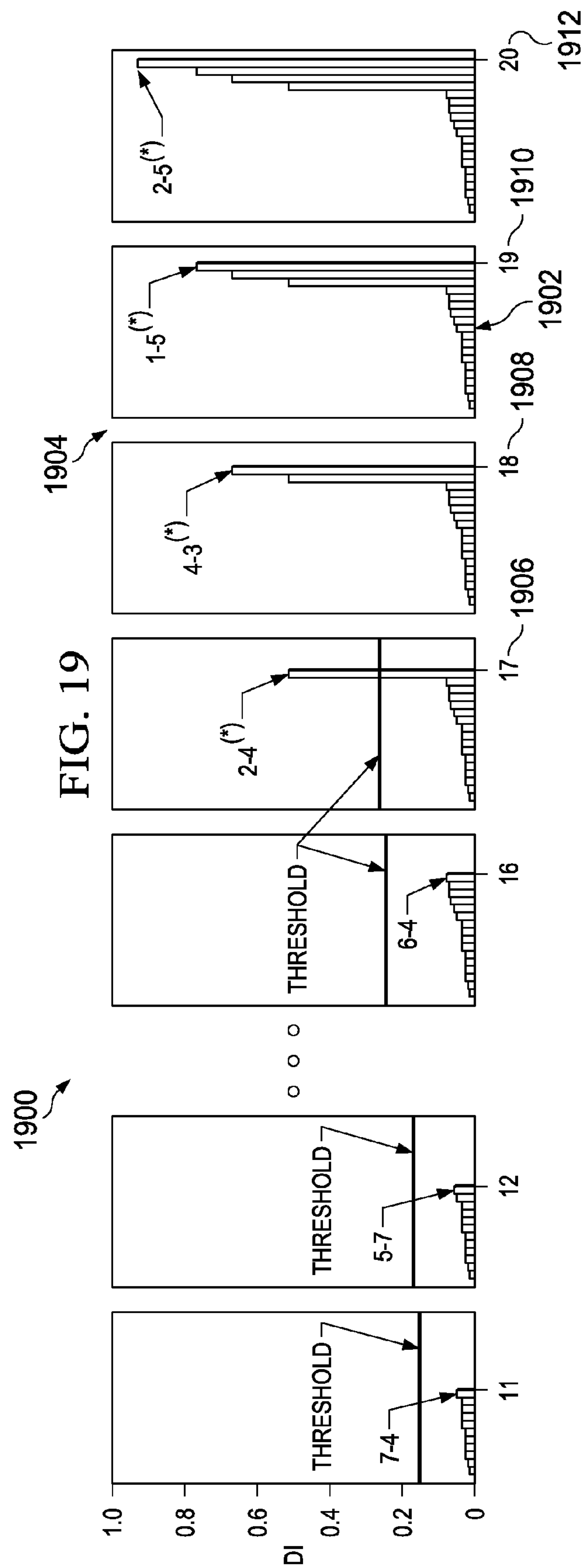

1700
1704
1800
1706
4-3
0-1
2-1
5-4
6-7
7-8
NORMALIZED AMPLITUDE
1
0
-1
0
0.05
0.10
0.15
0.20
TIME (ms)
1702
EXTRACTED A_0 MODES

FIG. 19


1900
1904
1902
1906
1908
1910
1912
DI
1.0
0.8
0.6
0.4
0.2
0
THRESHOLD
7-4
11
5-7
12
6-4
16
2-4(*)
17
4-3(*)
18
1-5(*)
19
2-5(*)
20

2000

CASE	DAMAGED LOCATION(S) (2010)	TEMPERATURE (°C) (2012)	THRESHOLD VALUE (2014)	DAMAGED PATH(S) (DI VALUE) (2016)
1 (2002)	0 (UNDAMAGE)	-10	0.164	NONE
		20	0.247	NONE
		50	0.276	NONE
2 (2004)	1 (DAMAGE 1)	-10	0.176	4-3(0.674)
		20	0.262	4-3(0.842)
		50	0.285	4-3(0.702)
3 (2006)	2 (DAMAGES 1,2)	-10	0.189	4-3(0.693), 2-5(0.923)
		20	0.274	4-3(0.778), 2-5(0.875)
		50	0.266	4-3(0.725), 2-5(0.926)
4 (2008)	3 (DAMAGES 1,2,3)	-10	0.147	2-4(0.375), 4-3(0.647) 1-5(0.807), 2-5(0.921)
		20	0.279	2-4(0.339), 4-3(0.737) 1-5(0.841), 2-5(0.862)
		50	0.261	2-4(0.508), 4-3(0.663) 1-5(0.764), 2-5(0.930)

FIG. 20

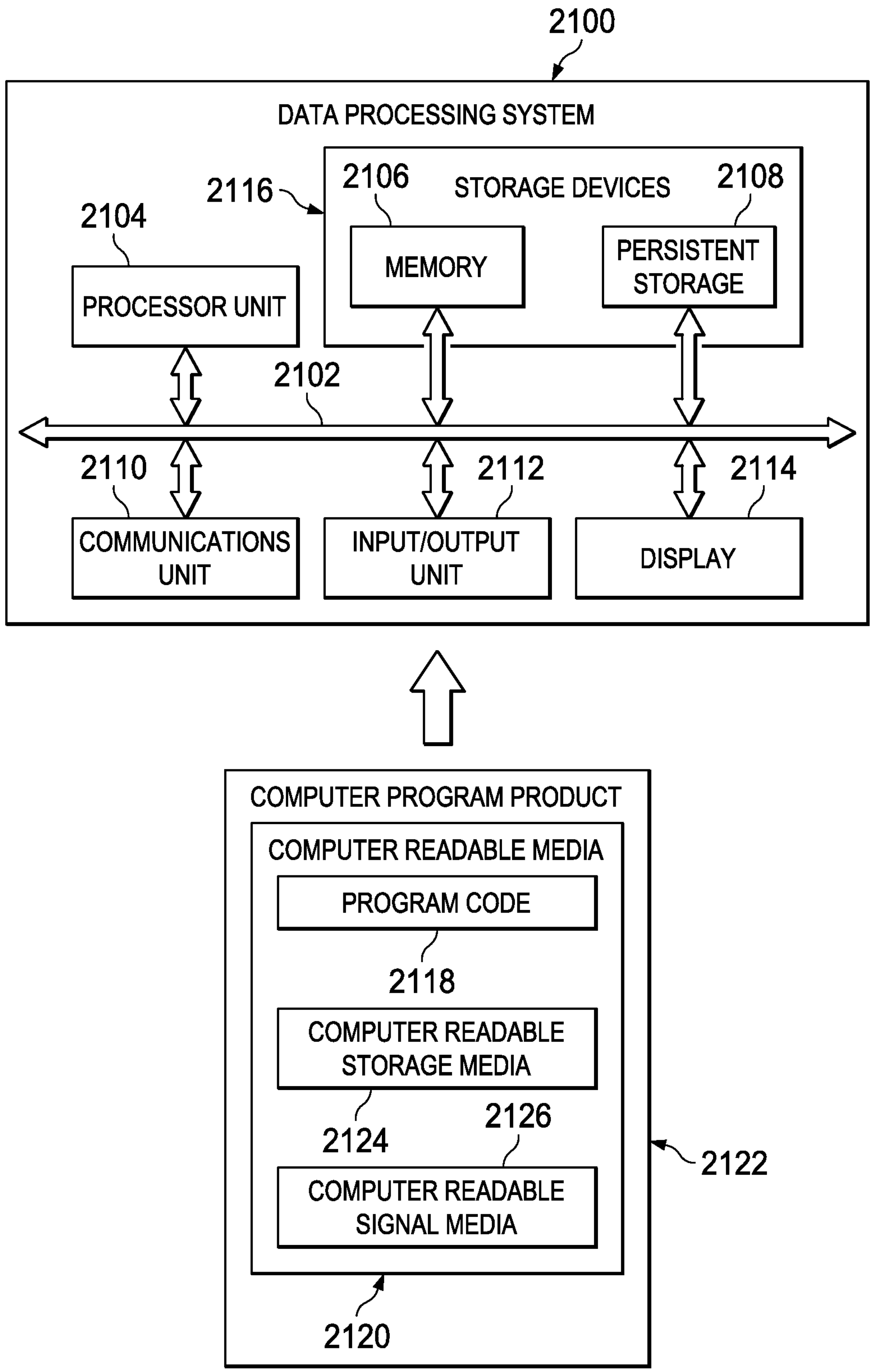

2100
DATA PROCESSING SYSTEM
2116
2106
STORAGE DEVICES
2108
2104
MEMORY
PERSISTENT STORAGE
PROCESSOR UNIT
2102
2110
2112
2114
COMMUNICATIONS UNIT
INPUT/OUTPUT UNIT
DISPLAY
COMPUTER PROGRAM PRODUCT
COMPUTER READABLE MEDIA
PROGRAM CODE
2118
COMPUTER READABLE STORAGE MEDIA
2124
2126
2122
COMPUTER READABLE SIGNAL MEDIA
2120

FIG. 21

TIME DELAY BASED HEALTH MONITORING SYSTEM USING A SENSOR NETWORK

RELATED PROVISIONAL APPLICATION

This application is related to and claims the benefit of priority of provisional U.S. Patent Application Ser. No. 61/449,577, filed Mar. 4, 2011, entitled "Time Delay Based Health Monitoring System Using a Sensor Network", which is incorporated herein by reference.

CROSS-REFERENCE TO RELATED APPLICATION

This application is related to the following patent application entitled: "Transducer Based Health Monitoring System", Ser. No. 13/083,957; filed even date hereof, assigned to the same assignee, and incorporated herein by reference.

BACKGROUND INFORMATION

1. Field

The present disclosure relates generally to monitoring aircraft structures and, in particular, to monitoring aircraft structures for inconsistencies. Still more particularly, the present disclosure relates to a method and apparatus for detecting inconsistencies in aircraft structures using signals sent through the aircraft structures.

2. Background

Composite and metallic aircraft structures may be susceptible to internal changes that may occur from fatigue, impacts, and/or other events or conditions. Composite materials typically have a minimal visual indication of these types of changes. As a result, an aircraft may be inspected to assess the integrity of the structure on a periodic basis, or after visual indications of surface inconsistencies, such as a dent or a scratch.

For example, impacts to a structure, such as an aircraft, may occur during cargo loading and unloading. Inspections of the structure of an aircraft may be time consuming and costly in terms of the time and skill needed to perform the inspection. Further, an airline may incur a loss of revenue from the aircraft being out of service.

Structural health monitoring techniques have been developed and used to monitor materials and structures. These techniques often build the health monitoring systems into the structures. These health monitoring systems may be used to determine whether changes have occurred to these materials and structures over time.

Sudden changes in environments, such as electromagnetic effects, mechanical stresses, and other environmental effects may affect various materials and structures over time. By having health monitoring systems built into or associated with the structures to monitor the structures during use, appropriate measures and responses may be taken to prevent inconsistencies and may prolong the life span of these structures.

The monitoring of these structures may include various non-destructive elevation methods, such as ultrasonic testing or x-ray testing. Ultrasonic testing uses contact-based transducers to mechanically scan a structure. These sensors and actuators may be surface-mounted on the structure or may be embedded in the structure to generate and propagate signals into the structure being monitored.

A structural health monitoring system uses transducers to transmit waveforms at various frequency ranges and acquire

data from the responses. Although structural health monitoring systems may provide an automated onboard system for detecting and characterizing inconsistencies or changes that may require maintenance, these types of systems may require updates and adjustments when maintenance, modifications, and reconfigurations of an aircraft occur.

For example, if a skin panel is changed, if a landing gear is modified, or if other changes occur, additional transducers may need to be moved or configured for use with the replaced or new components. These and other types of updates to the structural health monitoring system are time-consuming and expensive. The time needed to update the health monitoring system may make the aircraft unavailable for use longer than desired.

Therefore, it would be advantageous to have a method and apparatus that takes into account at least some of the issues discussed above, as well as possibly other issues.

SUMMARY

In one advantageous embodiment, a method for detecting an inconsistency in an object is provided. Signals sent on a plurality of paths in the object are received at a plurality of transducer units associated with the object. Time delays are identified for a number of modes in the signals received at the plurality of transducer units. A determination is made as to whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays for the number of modes that is greater than a desired amount.

In another advantageous embodiment, an apparatus comprises a signal analysis module. The signal analysis module is configured to identify time delays for a number of modes in signals received at a plurality of transducer units. The signals are received on a plurality of paths in an object in which the plurality of transducer units is associated with the object. The signal analysis module is configured to determine whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays in the time delays for the number of modes in the signals that is greater than a desired amount.

In yet another advantageous embodiment, a health monitoring system of an aircraft comprises a transducer system and a signal analysis module. The transducer system is associated with a number of structures in the aircraft. The signal analysis module is configured to cause a first plurality of transducer units associated with the number of structures in the aircraft to send signals on a plurality of paths in an object. The signal analysis module is configured to identify time delays for asymmetric modes in the signals received by a second plurality of transducer units in the transducer system. The signal analysis module is configured to determine whether a time delay in the time delays for the asymmetric modes in the signals has a difference from a number of other time delays for the asymmetric modes that is greater than a desired amount.

The features, functions, and advantages can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the advantageous embodiments are set forth in the appended claims. The advantageous embodiments, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood with reference to the following detailed description of an advantageous embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

FIG. **1** is an illustration of an aircraft manufacturing and service method in accordance with an advantageous embodiment;

FIG. **2** is an illustration of an aircraft in which an advantageous embodiment may be implemented;

FIG. **3** is an illustration of a health monitoring environment in accordance with an advantageous embodiment;

FIG. **4** is an illustration of a signal analysis module in accordance with an advantageous embodiment;

FIG. **5** is an illustration of a transducer system in accordance with an advantageous embodiment;

FIG. **6** is an illustration of graphs identifying a time delay for a signal due to a presence of an inconsistency in accordance with an advantageous embodiment;

FIG. **7** is an illustration of three transducers for a transducer unit in accordance with an advantageous embodiment;

FIG. **8** is a two-segment transducer unit in accordance with an advantageous embodiment;

FIG. **9** is an illustration of a ring-based transducer in accordance with an advantageous embodiment;

FIG. **10** is an illustration of a ring transducer unit in accordance with an advantageous embodiment;

FIG. **11** is an illustration of signals detected by two different segments of a transducer unit in accordance with an advantageous embodiment;

FIG. **12** is an illustration of a flowchart of a process for detecting an inconsistency in an object in accordance with an advantageous embodiment;

FIG. **13** is a flowchart of a process for selecting modes in signals received at transducers in accordance with an advantageous embodiment;

FIG. **14** is an illustration of a classification process for paths in accordance with an advantageous embodiment;

FIG. **15** is an illustration of a top view of an experimental setup on a portion of an object for testing for inconsistencies in the object in accordance with an advantageous embodiment;

FIG. **16** is an illustration of a portion of a health monitoring system in accordance with an advantageous embodiment;

FIG. **17** is an illustration of a graph comparing extracted asymmetric modes for a group of paths in accordance with an advantageous embodiment;

FIG. **18** is an illustration of a graph comparing extracted asymmetric modes for a group of paths in accordance with an advantageous embodiment;

FIG. **19** is an illustration of a portion of the charts identifying index values for paths in accordance with an advantageous embodiment;

FIG. **20** is an illustration of a table containing the results of testing an object for inconsistencies under different conditions in accordance with an advantageous embodiment; and

FIG. **21** is an illustration of a data processing system in accordance with an advantageous embodiment.

DETAILED DESCRIPTION

Referring more particularly to the drawings, advantageous embodiments of the disclosure may be described in the context of aircraft manufacturing and service method **100** as shown in FIG. **1** and aircraft **200** as shown in FIG. **2**. Turning first to FIG. **1**, an illustration of an aircraft manufacturing and service method is depicted in accordance with an advantageous embodiment. During pre-production, aircraft manufacturing and service method **100** may include specification and design **102** of aircraft **200** in FIG. **2** and material procurement **104**.

During production, component and subassembly manufacturing **106** and system integration **108** of aircraft **200** in FIG. **2** takes place. Thereafter, aircraft **200** in FIG. **2** may go through certification and delivery **110** in order to be placed in service **112**. While in service **112** by a customer, aircraft **200** in FIG. **2** is scheduled for routine maintenance and service **114**, which may include modification, reconfiguration, refurbishment, and other maintenance or service.

Each of the processes of aircraft manufacturing and service method **100** may be performed and/or carried out by a system integrator, a third party, and/or an operator. In these examples, the operator may be a customer. For the purposes of this description, a system integrator may include, without limitation, any number of aircraft manufacturers and major-system subcontractors; a third party may include, without limitation, any number of vendors, subcontractors, and suppliers; and an operator may be an airline, a leasing company, a military entity, a service organization, and so on.

With reference now to FIG. **2**, an illustration of an aircraft is depicted in which an advantageous embodiment may be implemented. In this illustrative example, aircraft **200** is produced by aircraft manufacturing and service method **100** in FIG. **1** and may include airframe **202** with plurality of systems **204** and interior **206**. Examples of plurality of systems **204** include one or more of propulsion system **208**, electrical system **210**, hydraulic system **212**, environmental system **214**, and health monitoring system **216**. Any number of other systems may be included. Although an aerospace example is shown, different advantageous embodiments may be applied to other industries, such as the automotive industry.

Apparatuses and methods embodied herein may be employed during at least one of the stages of aircraft manufacturing and service method **100** in FIG. **1**. As used herein, the phrase "at least one of", when used with a list of items, means that different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, "at least one of item A, item B, and item C" may include, for example, without limitation, item A or item A and item B. This example may also include item A, item B, and item C or item B and item C.

In one illustrative example, components or subassemblies produced in component and subassembly manufacturing **106** in FIG. **1** for health monitoring system **216** may be fabricated or manufactured in a manner similar to components or subassemblies produced for health monitoring system **216** while aircraft **200** is in service **112** in FIG. **1**. As yet another example, a number of apparatus embodiments, method embodiments, or a combination thereof may be utilized during production stages, such as component and subassembly manufacturing **106** and system integration **108** in FIG. **1**. A "number", when referring to items, means "one or more items." For example, a number of apparatus embodiments is one or more apparatus embodiments. A number of apparatus embodiments, method embodiments, or a combination thereof may be utilized while aircraft **200** is in service **112** and/or during maintenance and service **114** in FIG. **1**. The use of a number of the different advantageous embodiments may substantially expedite the assembly of and/or reduce the cost of aircraft **200**.

The different advantageous embodiments recognize and take into account a number of different considerations. For example, the different advantageous embodiments recognize and take into account that many currently used health monitoring systems that use baseline data may have a higher rate of false positive indications of inconsistencies than desired. These false indications may occur from different environmental and operational variations.

For example, the different advantageous embodiments recognize and take into account that many currently used health monitoring systems rely on baseline data. Baseline data is data generated from sending signals through structures in the aircraft during a time at which the structures are considered to have no inconsistencies.

The different advantageous embodiments recognize and take into account that this baseline data is typically generated under conditions that may vary from those present during operating conditions. For example, the data may be generated using the temperature, pressure, and other environmental factors that are present, while the aircraft or parts are on the ground or not installed. These parameters may change when the aircraft is operating. The parameters may also change between various phases of flight such as taxiing, takeoff, en route, landing, and other phases. Temperature, pressure, and other changes in the environment around an aircraft during operation of the aircraft may result in false indications of the presence of inconsistencies when compared to baseline data taken during generation of the baseline data when the aircraft is not in operation.

The different advantageous embodiments recognize and take into account that currently used health monitoring systems may attempt to compensate for changes in the environment. The different advantageous embodiments recognize and take into account that currently used systems may attempt to obtain data for the structures without inconsistencies under the different operating conditions that may occur to take into account changes that may occur in the environment. This information may then be used as a comparison to data generated during the operation of the aircraft to determine whether inconsistencies are present.

The different advantageous embodiments recognize and take into account, however, that this type of compensation for operating conditions may require recording more data than desired. The amount of data obtained for different environmental conditions may use more storage space than desirable in a health monitoring system. Further, the different advantageous embodiments also recognize and take into account that it may not be possible to record data from all possible types of operating conditions that may be encountered during the operation of the aircraft.

The different advantageous embodiments also recognize and take into account that this type of health monitoring system may also require re-recording of data when sensors are replaced. The different advantageous embodiments recognize and take into account that it would be desirable to detect inconsistencies without requiring the use of baseline data.

Thus, the different advantageous embodiments provide a method and apparatus for detecting inconsistencies in an object. In one advantageous embodiment, signals sent on a plurality of paths in the object are received at a plurality of transducer units associated with the object. Time delays are identified for a number of modes in the signals received at the plurality of transducer units. A determination is made as to whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays for the number of modes that is greater than a desired amount.

With reference now to FIG. **3**, an illustration of a health monitoring environment is depicted in accordance with an advantageous embodiment. Health monitoring environment **300** is an example of an environment that may be implemented in aircraft **200** in FIG. **2**. As depicted, health monitoring environment **300** includes object **302** and health monitoring system **304** in this illustrative example.

In this illustrative example, object **302** is an example of an object that may be monitored using health monitoring system **304**. In this illustrative example, object **302** may take various forms. In this example, object **302** takes the form of aircraft **200** or a structure or system within aircraft **200** in FIG. **2**.

Health monitoring system **304** is associated with object **302**. A first component may be considered to be associated with a second component by being secured to the second component, bonded to the second component, fastened to the second component, and/or connected to the second component in some other suitable manner. The first component may also be connected to the second component using a third component. The first component may also be considered to be associated with the second component by being formed as part of and/or an extension of the second component.

In these depicted examples, health monitoring system **304** is configured to detect a presence of inconsistency **306** in object **302**. Inconsistency **306** may be any element or portion of object **302** that does not have a desired or expected state. Inconsistency **306** may be, for example, at least one of a delamination, a number of voids, and/or some other suitable type of inconsistency.

As depicted, health monitoring system **304** comprises transducer system **308** and signal analysis module **310**. Transducer system **308** comprises group of transducer units **312**. A transducer unit within group of transducer units **312** may function as a transmitter, a sensor, or both a transmitter and a sensor, depending on the particular implementation.

In these illustrative examples, group of transducer units **312** may be divided into first plurality of transducer units **316** and second plurality of transducer units **318**. First plurality of transducer units **316** may be configured to function as transmitters **321**. Second plurality of transducer units **318** may be configured to function as sensors **322**.

Each transducer unit in group of transducer units **312** may include one or more transducers depending on the particular implementation. Transducers within group of transducer units **312** may be implemented using any known transducer configured to generate signals that may be sent through object **302**. Additionally, transducers within group of transducer units **312** may also include transducers configured to receive signals **324** sent through object **302**.

In these illustrative examples, transducer system **308** is connected to signal analysis module **310**. Signal analysis module **310** is configured to control transducer system **308** in monitoring or testing object **302** for inconsistency **306**.

In these illustrative examples, signal analysis module **310** is comprised of hardware, software, or a combination of the two. For example, signal analysis module **310** may be comprised of number of computers **314** with software **315**.

Signal analysis module **310** is configured to cause first plurality of transducer units **316** to send signals **324** on plurality of paths **326**. Signals **324** travel on path **320** to second plurality of transducer units **318** in these depicted examples. In these illustrative examples, plurality of paths **326** have same direction **328**. Although plurality of paths **326** may have same direction **328**, lengths **330** for paths within plurality of paths **326** may be different.

In particular, in these illustrative examples, plurality of paths **326** have same direction **328** when object **302** comprises composite materials. Composite materials, particularly in aircraft structures, generally have directionality of wave propagation. In other words, different wave speeds occur depending on the direction of the wave propagation.

For composite materials, when plurality of paths **326** do not have same direction **328**, the arrival time of number of modes **340** may be unmated even if inconsistency **306** is not present in object **302**. Of course, in other illustrative examples, plurality of paths **326** may have different directions.

Signals **324** travel from first plurality of transducer units **316** to second plurality of transducer units **318** in times **332**. Times **332** are identified by signal analysis module **310**. Times **332** may also be referred to as times of flight or times of travel.

Additionally, signals **324** have plurality of modes **334**. In other words, each signal in signals **324** has plurality of modes **334**. A mode, as used herein, is a component of a waveform that makes up a signal in signals **324**. A mode is one type of physical propagation of waveforms in these illustrative examples.

In these illustrative examples, different modes within plurality of modes **334** for each signal of signals **324** may arrive at a sensor within second plurality of transducer units **318** at different times within times **332**. These times are also referred to as time delays **336**.

In these illustrative examples, signal analysis module **310** identifies time delays **338** for number of modes **340** in plurality of modes **334** for signals **324** received by second plurality of transducer units **318** in group of transducer units **312**. In these illustrative examples, one mode is selected for number of modes **340**. In other illustrative examples, additional modes may also be identified. Each time delay for a particular mode in number of modes **340** is identified for a particular path in plurality of paths **326**.

Time delays **338** may be identified by signal analysis module **310** in the form of velocities **342**. In other words, a velocity within velocities **342** is present for each mode in number of modes **340** for a particular path in plurality of paths **326**. For example, a velocity is present in velocities **342** for each path in plurality of paths **326** for a particular mode in number of modes **340** along that path.

In these illustrative examples, time delays **338** may be measured using velocities **342**. For example, when a signal in signals **324** is detected at second plurality of transducer units **318**, signal analysis module **310** identifies the velocity for a mode in number of modes **340** for the signal at the time of detection. A slower velocity for the mode for the signal as compared to the velocities for the same mode in other signals in signals **324** may indicate that inconsistency **306** was encountered along the path in plurality of paths **326** for the signal. In this manner, a slower velocity for the signal indicates a time delay for the mode that may be caused by inconsistency **306**. The velocity along with a length of the path may be used to calculate the time delay.

In this manner, lengths **330** for plurality of paths **326** may be different. As a result, normalizing for actual time in time delays **338** may be unnecessary when velocities **342** are used to represent time delays **338**. A velocity within velocities **342** that varies from other velocities represents a difference in time delay as compared to the other velocities.

In these illustrative examples, signal analysis module **310** is configured to determine whether time delay **344** in time delays **338** has difference **346** from other time delays **348** in time delays **338** that is greater than desired amount **350**. Time delay **344** is for a particular mode in number of modes **340** for a particular path associated with time delay **344**. In other words, difference **346** may be greater than other time delays **348** and time delays **338** for number of modes **340** when inconsistency **306** is present along the path associated with time delay **344**.

Signal analysis module **310** generates alert **352** if difference **346** of time delay **344** is greater than desired amount **350**. Alert **352** is an indication that inconsistency **306** is present in object **302**. In these illustrative examples, alert **352** may be a signal, a message, or some other suitable type of alert. Alert **352** may include other information. For example, alert **352** may include the particular path, the transmitting and receiving transducer, the time at which the inconsistency was detected, operating conditions, state of the aircraft, and other suitable information.

In some illustrative examples, time delays **338** for number of modes **340** may be identified without using velocities **342**. For example, time delays **338** for number of modes **340** for signals **324** may be identified by normalizing lengths **330** for plurality of paths **326** along which signals **324** travel from first plurality of transducer units **316** to second plurality of transducer units **318**. These normalized lengths may then be used to identify time delays **338**.

Thus, the different advantageous embodiments in health monitoring environment **300** identify a presence of inconsistency **306** without needing or using baseline data.

The illustration of health monitoring environment **300** in FIG. **3** is not meant to imply physical or architectural limitations to the manner in which different advantageous embodiments may be implemented. Other components in addition to and/or in place of the ones illustrated may be used. Some components may be unnecessary in some advantageous embodiments. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined and/or divided into different blocks when implemented in different advantageous embodiments.

For example, although object **302** has been described with respect to an aircraft, object **302** may take other forms. For example, object **302** may be selected from one of a mobile platform, a stationary platform, a land-based structure, an aquatic-based structure, a space-based structure, an aircraft, a surface ship, a tank, a personnel carrier, a train, a spacecraft, a space station, a satellite, a submarine, an automobile, a power plant, a bridge, a dam, a manufacturing facility, a building, a skin panel, an engine, a fuselage, a wing, a rib, and a stringer.

In yet other illustrative examples, additional signal analysis modules in addition to signal analysis module **310** may be present to provide for more coverage of object **302**, redundancy, or for some other suitable purpose. Further, health monitoring system **304** may be embedded or built into object **302** in some illustrative examples. In other illustrative examples, health monitoring system **304** may be connected to or attached to object **302** for monitoring object **302** for a period of time and then removed or detached from object **302**.

Additionally, although the different advantageous embodiments have been described for an object comprising composite materials, objects comprising other types of materials may also be tested using health monitoring system **304**.

For example, object **302** may comprise materials such as, without limitation, steel, titanium, aluminum, a metal alloy, and/or other suitable types of materials. When object **302** is comprised of materials other than composite materials, paths in plurality of paths **326** may not all have same direction **328**. In other words, paths in plurality of paths **326** may have different directions.

With reference now to FIG. **4**, an illustration of a signal analysis module is depicted in accordance with an advantageous embodiment. Signal analysis module **400** is an example of one implementation for signal analysis module **310** in FIG. **3**.

In this illustrative example, signal analysis module **400** includes mode selection unit **402**, time delay identification unit **404**, and classification unit **406**. These different units may be implemented in hardware, software, or a combination of the two. As one illustrative example, these units may be implemented within program code **410** running on number of computers **412**.

In this depicted example, signal generation unit **408** is configured to cause transducer units **414** to generate signals **416** that travel on plurality of paths **418** and are then detected by transducer units **420**. Transducer units **414** function as transmitters **422**, while transducer units **420** function as sensors **424**.

In these illustrative examples, signals **416** take the form of Lamb waves **426**. Lamb waves **426** are waves that propagate in solid media. For example, Lamb waves **426** may propagate within the thickness of an object, such as a plate, or other type of object. Signal **425** in signals **416** has modes **428**. Modes **428** include asymmetric modes **430** and symmetric modes **434**.

In these illustrative examples, asymmetric modes **430** may be affected more by certain types of inconsistencies in an object as compared to symmetric modes **434**. In particular, asymmetric modes **430** may be affected more by inconsistencies in the form of delaminations as compared to symmetric modes **434**.

In these illustrative examples, mode selection unit **402** identifies number of modes **436** in modes **428** for use in determining whether an inconsistency is present. In the depicted examples, number of modes **436** takes the form of asymmetric mode **437** in asymmetric modes **430**. Of course, in other examples, additional asymmetric modes may be selected in addition to asymmetric mode **437** depending on the particular implementation.

With delamination of composite materials, an asymmetric mode in signals **416** is affected more than a symmetric mode in symmetric modes **434**. Of course, for other types of materials, other modes may be selected in modes **428**.

Number of modes **436** is selected as modes that may provide a greatest desired ability to identify inconsistencies in the object.

In these illustrative examples, this identification of number of modes **436** is performed for each signal in signals **416**. After asymmetric mode **437** has been selected for signal **425** and the same asymmetric mode is selected for other signals in signals **416**, time delays **438** in the form of velocities **440** are identified by time delay identification unit **404**. In these illustrative examples, time delays **438** are used by classification unit **406** to generate index values **442**. Index values **442** are used by classification unit **406** to determine whether an inconsistency is present along one of plurality of paths **418**.

If any of index values **442** are greater than threshold **444**, alert **446** is generated by classification unit **406** to indicate the presence of an inconsistency. In these illustrative examples, threshold **444** may be selected as a value that indicates that an inconsistency is present. An index value in index values **442** that is greater than threshold **444** may be considered an outlier. The selection of threshold **444** and index values **442** may be performed using various known statistical analysis techniques.

The illustration of signal analysis module **400** in FIG. **4** is not meant to imply physical or architectural limitations to the manner in which signal analysis module **310** in FIG. **3** may be implemented. In other illustrative examples, the different units may be implemented as a single unit, or other subdivisions may be made depending on the particular implementation.

With reference now to FIG. **5**, an illustration of a transducer system is depicted in accordance with an advantageous embodiment. In this illustrative example, transducer system **500** is an example of one implementation of transducer system **308** in FIG. **3**. In this illustrative example, transducer units **502**, **504**, **506**, **508**, **510**, and **512** are associated with skin panel **514**. Skin panel **514** is a composite skin panel with composite layers in these illustrative examples. Skin panel **514** is an example of one implementation for object **302** or a portion of object **302** in FIG. **3**.

As depicted, transducer units **502**, **504**, and **506** function as transmitters, while transducer units **508**, **510**, and **512** function as sensors. In these illustrative examples, transducer unit **502** and transducer unit **508** form path **516**, transducer unit **504** and transducer unit **510** form path **518**, and transducer unit **506** and transducer unit **512** form path **520**. As can be seen in these illustrative examples, path **516**, path **518**, and path **520** extend in the direction of arrow **522**. All of these paths have the same direction.

Although the paths are illustrated as having the same length, these paths may have different lengths depending on the particular implementation. Also, in other tests, transducer units **502**, **504**, and **506** may become sensors while transducer units **508**, **510**, and **512** become transmitters. In this case, the paths formed between the transducer units have a direction that is in the opposite direction of arrow **522**. Of course, paths may be generated by other combinations of transducer units in these examples, having the same direction.

In this illustrative example, inconsistency **524** is present along path **520**. Inconsistency **524** takes the form of a delamination of layers within skin panel **514**.

Inconsistency **524** results in a time delay for signals sent along path **520** being greater than those sent along paths **516** and **518**. As a result, the velocity of a signal sent along path **520** will be less than the velocities of signals sent along paths **516** and **518**. This difference in velocities is used to identify the presence of inconsistency **524**.

With reference now to FIG. **6**, an illustration of graphs identifying a time delay for a signal due to a presence of an inconsistency is depicted in accordance with an advantageous embodiment. Asymmetric mode waveforms **600**, **601**, and **602** may be waveforms extracted from signals transmitted and received by transducer units.

In this illustrative example, asymmetric mode waveform **600** is the asymmetric mode extracted from a signal transmitted by transducer unit **502** along path **516** in FIG. **5**. Asymmetric mode waveform **601** is the asymmetric mode extracted from a signal transmitted by transducer unit **504** along path **518** in FIG. **5**. Asymmetric mode waveform **602** is the asymmetric mode extracted from a signal transmitted by transducer unit **506** along path **520** in FIG. **5**.

As illustrated, asymmetric mode waveforms **600**, **601**, and **602** are transmitted at substantially the same time. In particular, asymmetric mode waveforms **600**, **601**, and **602** are transmitted at initial transmission time **604** in this example.

Time **606** is the time it takes for asymmetric mode waveform **600** to reach transducer unit **508** along path **516** in FIG. **5**. Time **608** is the time it takes for asymmetric mode waveform **601** to reach transducer unit **510** along path **518** in FIG. **5**. Time **610** is the time it takes for asymmetric mode waveform **602** to reach transducer unit **512** along path **520** in FIG. **5**. Times **606**, **608**, and **610** may also be referred to as times of flight for asymmetric mode waveforms **600**, **601**, and **602**, respectively.

Time delay **612** is the difference between time **610** and time **608**. Time delay **612** is the same difference between time **610** and time **606**. With paths **516**, **518**, and **520** having substantially the same length, the presence of time delay **612** indicates that inconsistency **524** is present along path **520**. In other words, when one of times **606**, **608**, and **610** is not substantially the same as the other times, an inconsistency is present along the corresponding path in skin panel **514**. When times **606**, **608**, and **610** are substantially the same, an inconsistency is not present along the corresponding paths.

In this manner, the identification of inconsistencies does not require the use of prior baseline data. Further, this process may be performed to identify inconsistencies even under changing operational and environmental conditions of the object.

With reference now to FIGS. **7-10**, examples of transducer units are depicted in accordance with an advantageous embodiment. In FIG. **7**, an illustration of three transducers for a transducer unit is depicted in accordance with an advantageous embodiment. In this illustrative example, transducer unit **700** is shown in a top view and a side view. Transducer unit **700** comprises transducer **702**, **704**, and **706**. As can be seen, transducer unit **700** is symmetric along axis **708**.

In FIG. **8**, an illustration of a two-segment transducer unit is depicted in accordance with an advantageous embodiment. In this illustrative example, transducer unit **800** comprises segment **802** and segment **804**. Transducer unit **800** is symmetric about axis **806**.

With reference now to FIG. **9**, an illustration of a ring-based transducer is depicted in accordance with an advantageous embodiment. In this illustrative example, transducer unit **900** comprises segment **902** and segment **904**. Segment **902** is a ring segment. Segment **904** is a circular segment. Transducer unit **900** is symmetric about axis **906** in these examples.

With reference now to FIG. **10**, an illustration of a ring transducer unit is depicted in accordance with an advantageous embodiment. In this illustrative example, transducer unit **1000** comprises segment **1002** and segment **1004**. Segment **1002** is a ring segment. Segment **1004** is a circular segment. Transducer unit **1000** is symmetric about axis **1006** in these illustrative examples.

With reference now to FIG. **11**, an illustration of signals detected by two different segments of a transducer unit is depicted in accordance with an advantageous embodiment. In this illustrative example, transducer unit **1100** functions as a transmitter, while transducer unit **1102** functions as a sensor. Transducer unit **1100** has ring segment **1104** and circular segment **1106**, while transducer unit **1102** has ring segment **1108** and circular segment **1110**.

As depicted in this illustrative example, path **1112** is formed between transducer unit **1100** and transducer unit **1102**. Activation of different segments for the transducer units allows four different Lamb wave signals to be obtained.

For example, when ring segment **1104** of transducer unit **1100** is activated, signal **1114**, V_{rr}, is detected by ring segment **1108** of transducer unit **1102**. Further, when ring segment **1104** is activated, signal **1116**, V_{rc}, is detected by circular segment **1110** of transducer unit **1102**. Two different Lamb wave signals (not shown), V_{cr} and V_{cc}, may be obtained when circular segment **1106** of transducer unit **1100** is activated.

In this illustrative example, the modes for signal **1114** and signal **1116** may have substantially identical arrival times at ring segment **1108** and circular segment **1110**, respectively, but different amplitudes. Further, the amplitudes of the symmetric (S_0) modes and the asymmetric (A_0) modes change at different rates as the size of the segment in the transmitting transducer unit that transmits the signal and the size of the segment in the sensing transducer unit that detects the signal changes.

In other words, the amplitudes of the symmetric modes and the asymmetric modes change depending on which segment is activated to transmit in transducer unit **1100** and which segment is activated to detect in transducer unit **1102**.

Additionally, the rate at which the amplitude of each mode in the modes for the signal changes, with respect to the size of the particular segments in the transducer units, is not based on the distance between transducer unit **1100** and transducer unit **1102**.

Signal **1114** and signal **1116** may be used by, for example, signal analysis module **400** in FIG. **4** to identify a number of modes for which time delays may be identified. For example, signal **1114** and signal **1116** may be measured at ring segment **1108** and circular segment **1110** for transducer unit **1102**. The amplitudes of the symmetric modes in signal **1114** and signal **1116** are normalized such that the amplitudes of the symmetric modes are substantially equal.

The symmetric modes may then be removed by subtracting signal **1114**, V_{rr}, from signal **1116**, V_{rc}. In other words, the symmetric modes are subtracted from each other such that only the asymmetric mode remains. The asymmetric mode waveform formed by this subtraction does not preserve amplitude information. However, this signal does retain arrival time information for the asymmetric mode. In this manner, time delay information may be identified using the asymmetric mode waveform.

However, the asymmetric mode waveform contains information for the time of travel between transducer unit **1100** and transducer unit **1102**. In this manner, time delay information may be identified using the asymmetric mode waveform.

With reference now to FIG. **12**, an illustration of a flowchart of a process for detecting an inconsistency in an object is depicted in accordance with an advantageous embodiment. The process illustrated in FIG. **12** may be implemented in health monitoring environment **300** in FIG. **3**. In particular, this process may be implemented within signal analysis module **310** in FIG. **3**.

The process begins by sending signals on a plurality of paths in an object using a first plurality of transducer units (operation **1200**). This first plurality of transducer units functions as transmitters. Signals are received at a second plurality of transducers associated with the object (operation **1202**). The second plurality of transducer units functions as sensors.

The process then identifies time delays for a number of modes in the signals received by the second plurality of transducer units (operation **1204**). In this illustrative example, the number of modes includes one type of mode. The process then selects a time delay that has not yet been processed from the identified time delays (operation **1206**). A determination is then made as to whether a time delay in the time delays for the number of modes in the signals has a difference from the other time delays for the number of modes that is greater than a desired amount (operation **1208**).

If the time delay for the number of modes has a difference from the other time delays for the number of modes that is greater than the desired amount, the process generates an alert (operation **1210**) and terminates thereafter.

With reference again to operation **1208**, if the time delay for the number of modes has a difference from the other time delays for the number of modes that is not greater than the desired amount, a determination is made as to whether additional time delays are present that have not yet been processed (operation **1212**). If additional time delays are not present, the process terminates. Otherwise, the process returns to operation **1206** to select another time delay that has not yet been processed from the identified time delays.

With reference now to FIG. **13**, a flowchart of a process for selecting modes in signals received at transducers is depicted in accordance with an advantageous embodiment. The process illustrated in FIG. **13** may be implemented in signal analysis module **400** and, in particular, within mode selection unit **402** in signal analysis module **400** in FIG. **4**.

The process begins by identifying a group of paths having a substantially equal spacing and a same direction in an object (operation **1300**). In operation **1300**, the object may be, for example, a composite skin panel. The object may have a number of inconsistencies in the object.

The paths are formed by transducer units placed on or in the object. In particular, the paths are formed along the distances between pairs of transducer units. For example, a signal transmitted by a transducer unit functioning as a transmitter travels along a path to a transducer unit functioning as a sensor. The transducer unit functioning as the sensor detects and measures the signal.

In this illustrative example, the transducer units may be any of a number of different forms having a number of segments. In one illustrative example, the transducer units take the form of, for example, transducer unit **800** in FIG. **8**, transducer unit **900** in FIG. **9**, transducer unit **1100** in FIG. **11**, and/or transducer unit **1102** in FIG. **11**. In other words, each of the transducer units forming the paths identified may have a ring segment and a circular segment. Of course, in other illustrative examples, other types of transducer units having segments with other types of shapes may be used.

The process selects a path from the identified group of paths for processing (operation **1302**). The process then identifies a first signal detected by a first segment of the sensing transducer unit (operation **1304**). The first segment may be a ring segment. The process identifies a second signal detected by a second segment of the sensing transducer unit (operation **1306**). The second segment may be a circular segment. In this illustrative example, the first signal and the second signal may be detected by the first segment and the second segment, respectively, at substantially the same time.

Thereafter, the process normalizes the amplitudes for the symmetric modes of the first signal and the second signal such that the normalized amplitudes for the symmetric modes are substantially equal (operation **1308**). The process then subtracts the first signal from the second signal to form a new signal (operation **1310**).

Next, the new signal is processed to extract an asymmetric mode waveform for the path (operation **1312**). The asymmetric mode waveform contains information about the amount of time the first signal and the second signal take traveling along the path from the transmitting transducer unit to the sensing transducer unit.

The process then determines whether any additional unprocessed paths are present in the group of paths identified (operation **1314**). If additional unprocessed paths are not present, the process terminates. Otherwise, the process returns to operation **1302** as described above.

The process illustrated in FIG. **13** may be performed for each group of paths that are substantially equally spaced and have a same direction.

With reference now to FIG. **14**, an illustration of a classification process for paths is depicted in accordance with an advantageous embodiment. The process illustrated in FIG. **14** may be implemented in classification unit **406** in signal analysis module **400** in FIG. **4**. Further, this process may be implemented after the process illustrated in FIG. **13**.

The process begins by calculating an index value for each path in a group of paths (operation **1400**). In operation **1400**, the group of paths is the group of paths identified in operation **1300** in FIG. **13**.

The index value is calculated to identify the time delay for the asymmetric mode identified for each path. The index value is calculated based on an assumption that more than half of the paths in the group of paths are along portions of the object without inconsistencies.

The index value may be calculated using the following equations:

$$DI(i,\Omega)=\frac{1}{2}\left(1-\frac{2}{n_d}\sum_{j}^{n_d/2}\mathrm{corr}(A_0(i,\Omega),A_0(j,\Omega))\right)$$

$$DI(i)=\frac{1}{N}\sum_{\Omega}^{N}DI(I,\Omega).$$

where DI is the index value, i is an identifier for a particular path, Ω is an input frequency, d is an identifier for the group of paths, n_d is the number of paths in a group of paths, corr is the cross-correlation function, j is the identifier for a path along which an inconsistency is not present, A_0 is the asymmetric mode, and $A_0(i, \Omega)$ and $A_0(j, \Omega)$ are the first arrival asymmetric modes at the input frequency Ω in the i and j paths, respectively. The j paths are selected as the half of the asymmetrical modes that are the fastest asymmetrical modes in the group of paths d.

In these illustrative examples, the first arrival asymmetric mode or the first arrival A_0 mode is a first asymmetric mode that arrives at the sensor. For example, the signals received at a sensor often include multiple modes. These modes may be, for example, directly propagated waves from a transmitter and a sensor, reflections from the structural boundary of the object, and/or from other types of sources. If an inconsistency is present between the sensor and the transmitter, only the first arrival A_0 mode is affected.

The index value DI indicates how much a signal traveling along a particular path is delayed as compared with other paths along which inconsistencies are not present.

The index value DI is normalized to have a range between 0 and 1 by subtracting the cross-correlation values from one and dividing it by 2. If the asymmetric mode obtained for a particular path has a similar arrival time with the asymmetric modes obtained for other paths along which inconsistencies are assumed to not be present, the index value approaches 0. Otherwise, if the asymmetric mode is delayed, the corresponding index value approaches 1.

Thereafter, the process arranges all of the index values calculated in an ascending order (operation **1402**). In the ascending order, the first index value is the smallest index value and the N^{th} index value is the largest index value. The N^{th} index value is the last index value. In this illustrative example, N is the total number of index values. Further, each index value is for a particular path. In this manner, N is the total number of paths.

Next, the process selects a first n^{th} smallest index value for analysis (operation **1403**). In this example, n is an identifier for a particular index value in the group of index values. In operation **1403**, the first index value may be selected as about half of the total number of paths. For example, if 20 paths are in the group of paths, the first n is selected as 10. In this manner, the 10^{th} smallest index value is selected as the first index value for analysis.

The process then fits a parametric distribution function to the n−1 smallest index value (operation **1404**). For example, in operation **1404**, when the 10^{th} index value is selected, a parametric distribution function is fitted to the nine smallest index values in the group of index values.

A truncated exponential distribution is used for the parametric distribution function in this illustrative example. This distribution is bounded because the index values have the upper limit of 1 and the lower limit of 0. A truncated exponential distribution with parameter c has the following probability density function:

$$f(x)=ce^{-cx}(1-e^{-c})^{-1},(0<x\leq 1).$$

where f(x) is the probability density function, e is the exponential function, and x is the index value. Further, the maximum likelihood estimator of c is denoted as c_b. The maximum likelihood estimator c_b can estimate a parameter of c of the best-fit truncated exponential distribution of x as follows:

$$\bar{x} = 1/c_b - 1/(e^{c_b} - 1).$$

where

$$\bar{x}$$

is the mean of x.

The process then identifies a threshold value for the n^{th} index value (operation **1406**). In operation **1406**, the threshold value is identified based on fitting the parametric distribution function to the n−1 smallest index values in operation **1404** and a specific confidence level. This confidence level may be set by user input.

Next, the process determines whether the value of the n^{th} smallest index value is greater than the threshold value (operation **1408**). If the value of the n^{th} smallest index value is not greater than the threshold value, the process determines whether n is equal to the total number of index values, N (operation **1410**). If n is not equal to the total number of index values, N, the process increments n (operation **1412**). Then the process returns to operation **1404** as described above.

With reference again to operation **1410**, if n is equal to the total number of index values, N, the process terminates. Further, with reference again to operation **1408**, if the value of the n^{th} smallest index value is greater than the threshold value, the process identifies the paths associated with the n^{th}, $n+1^{th}$, . . . N^{th} index values as having inconsistencies along the paths (operation **1414**), with the process terminating thereafter.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatus and methods in different advantageous embodiments. In this regard, each block in the flowchart or block diagrams may represent a module, segment, function, and/or a portion of an operation or step. For example, one or more of the blocks may be implemented as program code, in hardware, or a combination of the program code and hardware. When implemented in hardware, the hardware may, for example, take the form of integrated circuits that are manufactured or configured to perform one or more operations in the flowcharts or block diagrams.

In some alternative implementations, the function or functions noted in the block may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

With reference now to FIG. **15**, an illustration of a top view of an experimental setup on a portion of an object for testing for inconsistencies in the object is depicted in accordance with an advantageous embodiment. In this illustrative example, object **1500** is an example of object **302** in FIG. **3** that may be tested for inconsistencies. Object **1500** is a composite skin panel in this illustrative example. In particular, object **1500** is a carbon fiber composite skin panel.

As depicted, transducer units **1502**, **1504**, **1506**, **1508**, **1510**, **1512**, **1514**, **1516**, and **1518** are placed on object **1500**. These transducer units take the form of piezoelectric transducer (PZT) units. These transducer units are installed on surface **1515** of object **1500** in a square grid pattern having a spacing of about 15 centimeters.

In this illustrative example, transducer units **1502**, **1504**, **1506**, **1508**, **1510**, **1512**, **1514**, **1516**, and **1518** are arranged with substantially equal spacing. However, in other examples, these transducer units may have different distances from each other.

As depicted, various groups of paths may be formed by these transducer units. For example, groups **1520**, **1522**, **1524**, and **1526** may be formed by the transducer units. In this illustrative example, each group only includes paths that are substantially equally spaced from other paths in the group and paths that have the same direction. Each group includes five paths. In this manner, a total number of 20 paths are formed by the transducer units.

Further, as depicted, object **1500** may have inconsistencies **1528**, **1530**, and **1532**. Each of these inconsistencies may be, for example, a delamination of the composite skin panel. These inconsistencies may be located along some of the paths formed by the transducer units. For example, inconsistency **1528** is present along path **1534** in group **1520**. These inconsistencies may be caused by undesired temperatures for object **1500**.

With reference now to FIG. **16**, an illustration of a portion of a health monitoring system is depicted in accordance with an advantageous embodiment. In this illustrative example, health monitoring system **1600** is an example of one implementation for health monitoring system **304** in FIG. **3**. Only a portion of health monitoring system **1600** is depicted in this illustrative example. Health monitoring system **1600** includes transducer units **1502**, **1504**, **1506**, **1508**, **1510**, **1512**, **1514**, **1516**, and **1518** in FIG. **15**, but are not shown in this view.

As depicted, health monitoring system **1600** includes arbitrary waveform generator **1602**, high speed signals digitizer **1604**, low noise preamplifier **1606**, power amplifier **1608**, multiplexers **1610**, and controller **1612**. These components are used to generate signals that are transmitted in object **1500** in FIG. **15** by a first portion of transducer units **1502**, **1504**, **1506**, **1508**, **1510**, **1512**, **1514**, **1516**, and **1518** in FIG. **15** and detected and measured by a second portion of these transducer units. These signals are sent into object **1500** to identify the effects of inconsistencies **1528**, **1530**, and **1532** on Lamb wave modes.

With reference now to FIG. **17**, an illustration of a graph comparing extracted asymmetric modes for a group of paths is depicted in accordance with an advantageous embodiment. In this illustrative example, graph **1700** includes horizontal axis **1702** and vertical axis **1704**. Horizontal axis **1702** is time in milliseconds. Vertical axis **1704** is normalized amplitude for the asymmetric modes.

As depicted, curves **1706** are for the asymmetric modes extracted for a group of paths. These asymmetric modes may be extracted using the process illustrated in FIG. **13**, for example. The asymmetric modes are extracted from signals traveling along paths in group **1520** at a temperature of about 50 degrees Celsius.

In this illustrative example, curves **1706** are for the asymmetric modes for paths in group **1520** in FIG. **15**. In particular, curves **1706** are for group **1520** before any inconsistencies are present for object **1500**. More specifically, curves **1706** are for group **1520** before inconsistency **1528** is present along path **1534** in FIG. **15**.

As depicted, the arrival times for the asymmetric modes are substantially the same. In other words, in this illustrative example, a time delay is not present along the paths in group **1520** when an inconsistency is not present along the paths in group **1520**.

With reference now to FIG. **18**, an illustration of a graph comparing extracted asymmetric modes for a group of paths is depicted in accordance with an advantageous embodiment. In this illustrative example, curves **1706** in graph **1700** are for the asymmetric modes extracted for the paths in group **1520** in FIG. **15** when inconsistency **1528** is present along path **1534**.

As depicted, the presence of inconsistency **1528** along path **1534** causes curve **1800** for the asymmetric mode extracted for path **1534** to be shifted to the right of the other curves in curves **1706**. In other words, the arrival time for the asymmetric mode for path **1534** is delayed as compared to the arrival times for the other asymmetric modes for the other paths in group **1520**. In this manner, the time delay identified using the asymmetric modes provides an indicator of the presence of an inconsistency.

With reference now to FIG. **19**, an illustration of a portion of the charts identifying index values for paths is depicted in accordance with an advantageous embodiment. In this illustrative example, graphs **1900** provide an indication of which paths in the paths formed by transducer units **1502**, **1504**, **1506**, **1508**, **1510**, **1512**, **1514**, **1516**, and **1518** in FIG. **15** have inconsistencies present along the paths.

Graphs **1900** have horizontal axes **1902** and vertical axes **1904**. The horizontal axes are identifiers for index values calculated using cross-correlation. For example, these index values may be calculated in operation **1400** in FIG. **14**. The identifiers for the index values range from 1 to 20 because each index value is for a particular path in the 20 paths formed by transducer units **1502**, **1504**, **1506**, **1508**, **1510**, **1512**, **1514**, **1516**, and **1518** in FIG. **15**.

Further, the index values are arranged in ascending order such that the first index value is the smallest index value and the twentieth index value is the twentieth smallest index value or the largest index value. In this illustrative example, charts for only some of the index values for the paths are depicted.

Inconsistencies are identified as being present along a path when an index value is greater than a threshold. This threshold is calculated each time a new index value is taken into consideration.

As depicted, in this illustrative example, inconsistencies are identified as being present along the paths corresponding to seventeenth smallest index value **1906**, eighteenth smallest index value **1908**, nineteenth smallest index value **1910**, and twentieth smallest index value **1912**.

With reference now to FIG. **20**, an illustration of a table containing the results of testing an object for inconsistencies under different conditions is depicted in accordance with an advantageous embodiment. In this illustrative example, table **2000** contains the results of testing object **1500** in FIG. **15** for inconsistencies under various conditions.

Case 1 **2002** is the test case for when inconsistencies are not present in object **1500**. Case 2 **2004** is the test case for when only one inconsistency, such as inconsistency **1528** in FIG. **15**, is present in object **1500**. Case 3 **2006** is the test case for when two inconsistencies, such as inconsistency **1528** and inconsistency **1530** in FIG. **15**, are present in object **1500**. Case 4 **2008** is the test case for when three inconsistencies, such as inconsistency **1528**, inconsistency **1530**, and inconsistency **1532** in FIG. **15**, are present in object **1520**.

Inconsistency locations **2010** identify the number of locations at which inconsistencies have been introduced in object **1500** for each case. Temperature **2012** identifies the different temperatures at which the different cases were tested.

Threshold value **2014** identifies the threshold value at which a first path corresponding to an index value is identified as having an inconsistency when the index values are arranged in the ascending order. Path and index value **2016** identify the particular paths with corresponding index values for which inconsistencies are identified as being present along the path.

As indicated by the data presented in table **2000**, the method used for identifying inconsistencies in object **1500** accurately identifies inconsistency **1528**, inconsistency **1530**, and/or inconsistency **1532** at various temperatures. In particular, these inconsistencies are identified even at high temperatures, up to about 50 degrees Celsius, and low temperatures, up to about negative 10 degrees Celsius.

Turning now to FIG. **21**, an illustration of a data processing system is depicted in accordance with an advantageous embodiment. In this illustrative example, data processing system **2100** may be used to implement one or more of number of computers **314** in FIG. **3**. As depicted, data processing system **2100** includes communications fabric **2102**, which provides communications between processor unit **2104**, memory **2106**, persistent storage **2108**, communications unit **2110**, input/output (I/O) unit **2112**, and display **2114**.

Processor unit **2104** serves to execute instructions for software that may be loaded into memory **2106**. Processor unit **2104** may be a number of processors, a multi-processor core, or some other type of processor, depending on the particular implementation. A "number", as used herein with reference to an item, means "one or more items." Further, processor unit **2104** may be implemented using a number of heterogeneous processor systems in which a main processor is present with secondary processors on a single chip. As another illustrative example, processor unit **2104** may be a symmetric multi-processor system containing multiple processors of the same type.

Memory **2106** and persistent storage **2108** are examples of storage devices **2116**. A storage device is any piece of hardware that is capable of storing information, such as, for example, without limitation, data, program code in functional form, and/or other suitable information either on a temporary basis and/or a permanent basis. Storage devices **2116** may also be referred to as computer readable storage devices in these examples. Memory **2106**, in these examples, may be, for example, a random access memory or any other suitable volatile or non-volatile storage device. Persistent storage **2108** may take various forms, depending on the particular implementation.

For example, persistent storage **2108** may contain one or more components or devices. For example, persistent storage **2108** may be a hard drive, a flash memory, a rewritable optical disk, a rewritable magnetic tape, or some combination of the above. The media used by persistent storage **2108** may also be removable. For example, a removable hard drive may be used for persistent storage **2108**.

Communications unit **2110**, in these examples, provides for communications with other data processing systems or devices. In these examples, communications unit **2110** is a network interface card. Communications unit **2110** may provide communications through the use of either or both physical and wireless communications links.

Input/output unit **2112** allows for input and output of data with other devices that may be connected to data processing system **2100**. For example, input/output unit **2112** may provide a connection for user input through a keyboard, a mouse, and/or some other suitable input device. Further, input/output unit **2112** may send output to a printer. Display **2114** provides a mechanism to display information to a user.

Instructions for the operating system, applications, and/or programs may be located in storage devices **2116**, which are in communication with processor unit **2104** through communications fabric **2102**. In these illustrative examples, the instructions are in a functional form on persistent storage **2108**. These instructions may be loaded into memory **2106** for execution by processor unit **2104**. The processes of the different embodiments may be performed by processor unit **2104** using computer implemented instructions, which may be located in a memory, such as memory **2106**.

These instructions are referred to as program code, computer usable program code, or computer readable program code that may be read and executed by a processor in processor unit **2104**. The program code in the different embodiments may be embodied on different physical or computer readable storage media, such as memory **2106** or persistent storage **2108**.

Program code **2118** is located in a functional form on computer readable media **2120** that is selectively removable and may be loaded onto or transferred to data processing system **2100** for execution by processor unit **2104**. Program code **2118** and computer readable media **2120** form computer program product **2122** in these examples. In one example, computer readable media **2120** may be computer readable storage media **2124** or computer readable signal media **2126**. Computer readable storage media **2124** may include, for example, an optical or magnetic disk that is inserted or placed into a drive or other device that is part of persistent storage **2108** for transfer onto a storage device, such as a hard drive, that is part of persistent storage **2108**. Computer readable storage media **2124** may also take the form of a persistent storage, such as a hard drive, a thumb drive, or a flash memory that is connected to data processing system **2100**. In some instances, computer readable storage media **2124** may not be removable from data processing system **2100**. In these examples, computer readable storage media **2124** is a physical or tangible storage device used to store program code **2118** rather than a medium that propagates or transmits program code **2118**. Computer readable storage media **2124** is also referred to as a computer readable tangible storage device or a computer readable physical storage device. In other words, computer readable storage media **2124** is a media that can be touched by a person.

Alternatively, program code **2118** may be transferred to data processing system **2100** using computer readable signal media **2126**. Computer readable signal media **2126** may be, for example, a propagated data signal containing program code **2118**. For example, computer readable signal media **2126** may be an electromagnetic signal, an optical signal, and/or any other suitable type of signal. These signals may be transmitted over communications links, such as wireless communications links, optical fiber cable, coaxial cable, a wire, and/or any other suitable type of communications link. In other words, the communications link and/or the connection may be physical or wireless in the illustrative examples.

In some advantageous embodiments, program code **2118** may be downloaded over a network to persistent storage **2108** from another device or data processing system through computer readable signal media **2126** for use within data processing system **2100**. For instance, program code stored in a computer readable storage medium in a server data processing system may be downloaded over a network from the server to data processing system **2100**. The data processing system providing program code **2118** may be a server computer, a client computer, or some other device capable of storing and transmitting program code **2118**.

The different components illustrated for data processing system **2100** are not meant to provide architectural limitations to the manner in which different embodiments may be implemented. The different advantageous embodiments may be implemented in a data processing system including components in addition to or in place of those illustrated for data processing system **2100**. Other components shown in FIG. **21** can be varied from the illustrative examples shown. The different embodiments may be implemented using any hardware device or system capable of running program code. As one example, the data processing system may include organic components integrated with inorganic components and/or may be comprised entirely of organic components excluding a human being. For example, a storage device may be comprised of an organic semiconductor.

In another illustrative example, processor unit **2104** may take the form of a hardware unit that has circuits that are manufactured or configured for a particular use. This type of hardware may perform operations without needing program code to be loaded into a memory from a storage device or to be configured to perform the operations.

For example, when processor unit **2104** takes the form of a hardware unit, processor unit **2104** may be a circuit system, an application specific integrated circuit (ASIC), a programmable logic device, or some other suitable type of hardware configured to perform a number of operations. With a programmable logic device, the device is configured to perform the number of operations. The device may be reconfigured at a later time or may be permanently configured to perform the number of operations. Examples of programmable logic devices include, for example, a programmable logic array, a programmable array logic, a field programmable logic array, a field programmable gate array, and other suitable hardware devices. With this type of implementation, program code **2118** may be omitted because the processes for the different embodiments are implemented in a hardware unit.

In still another illustrative example, processor unit **2104** may be implemented using a combination of processors found in computers and hardware units. Processor unit **2104** may have a number of hardware units and a number of processors that are configured to run program code **2118**. With this depicted example, some of the processes may be implemented in the number of hardware units, while other processes may be implemented in the number of processors.

In another example, a bus system may be used to implement communications fabric **2102** and may be comprised of one or more buses, such as a system bus or an input/output bus. Of course, the bus system may be implemented using any suitable type of architecture that provides for a transfer of data between different components or devices attached to the bus system.

Additionally, a communications unit may include a number of one or more devices that transmit data, receive data, or transmit and receive data. A communications unit may be, for example, a modem or a network adapter, two network adapters, or some combination thereof. Further, a memory may be, for example, memory **2106**, or a cache, such as found in an interface and memory controller hub that may be present in communications fabric **2102**.

Thus, the different advantageous embodiments provide a method and apparatus for detecting an inconsistency in an object. In one advantageous embodiment, a method for detecting an inconsistency in an object is provided. Signals sent on a plurality of paths in the object are received at a plurality of transducer units associated with the object. Time delays are identified for a number of modes in the signals received at the plurality of transducer units. A determination is made as to whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays for the number of modes that is greater than a desired amount.

The different advantageous embodiments provide a detection apparatus and process that does not rely on pre-existing data. In other words, baseline data for the object without inconsistencies is unnecessary. Thus, the storage space for baseline data and generating baseline data for an object at various temperatures and other environmental conditions also is unnecessary. As a result, the time and expense needed for monitoring an object may be reduced.

In one or more of the advantageous embodiments, inconsistencies are detected without any comparison with previously obtained baseline data. This type of identification of inconsistencies may be performed even in the presence of environmental variations, such as, for example, without limitation, temperature, pressure, and/or other environmental changes. In some advantageous embodiments, velocities are identified from signals sent through an object during a current state for a structure. These velocities are used to determine whether an inconsistency is present in the object. Baseline or other comparisons formed at prior times based on different environmental conditions are not used. As a result, the identification of an inconsistency is not affected by environmental conditions.

The description of the different advantageous embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the advantageous embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art.

Further, different advantageous embodiments may provide different advantages as compared to other advantageous embodiments. The advantageous embodiment or embodiments selected are chosen and described in order to best explain the principles of the advantageous embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various advantageous embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. A method for detecting an inconsistency in an object, the method comprising:

receiving signals sent on a plurality of paths in the object at a plurality of transducer units associated with the object;

identifying time delays for a number of modes in the signals received at the plurality of transducer units; and

determining whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays for the number of modes that is greater than a desired amount.

2. The method of claim **1**, wherein the determining step comprises:

determining whether an inconsistency is present based on whether the time delay in the time delays for the number of modes in the signals has the difference from the number of other time delays for the number of modes that is greater than the desired amount.

3. The method of claim **1** further comprising:

identifying a path in the plurality of paths corresponding to the time delay as having an inconsistency in response to the time delay having the difference that is greater than the desired amount.

4. The method of claim **1**, wherein the identifying step comprises:

identifying velocities for the number of modes in the signals received at the plurality of transducer units, wherein a comparison of the velocities with each other is used to identify the time delays; and

wherein the determining step comprises:

determining whether a velocity in the velocities for the number of modes in the signals has a difference from other velocities in the velocities that is greater than the desired amount.

5. The method of claim **4**, wherein the determining step comprises:

performing a statistical analysis for the velocities to form a plurality of index values; and

determining whether the velocity in the velocities is an outlier.

6. The method of claim **1**, wherein the signals are sent on the plurality of paths using the plurality of transducer units.

7. The method of claim **1**, wherein the determining step comprises:

generating an index value for the number of modes for each path in the plurality of paths to form a plurality of index values, wherein the index value provides an indication of the time delay corresponding to the each path;

identifying a threshold value, wherein an inconsistency is identified as being present if the index value is greater than the threshold value;

comparing the index value in the plurality of index values with the threshold; and

identifying a set of index values that are greater than the threshold.

8. The method of claim **1**, wherein a transducer unit in the plurality of transducer units is selected from one of a transducer having a first plurality of segments configured to receive particular signals received on a path in the plurality of paths and a second transducer having a second plurality of segments configured to send the particular signals received on the path in the plurality of paths.

9. The method of claim **1**, wherein the number of modes are selected as a particular number of modes in which a longer time delay is present for a particular path when an inconsistency is present along the particular path as compared to when the inconsistency is absent from the particular path.

10. The method of claim **1**, wherein the number of modes comprises an asymmetric mode and wherein the plurality of paths are substantially equally spaced apart relative to each other.

11. The method of claim **1**, wherein the object is selected from one of a mobile platform, a stationary platform, a land-based structure, an aquatic-based structure, a space-based structure, an aircraft, a surface ship, a tank, a personnel carrier, a train, a spacecraft, a space station, a satellite, a submarine, an automobile, a power plant, a bridge, a dam, a manufacturing facility, a building, a skin panel, an engine, a fuselage, a wing, a rib, and a stringer.

12. The method of claim **1**, wherein the plurality of paths has a same direction.

13. A health monitoring system comprising:

a plurality of transducer units configured to receive signals from an object; and

a signal analysis module configured to identify time delays for a number of modes in the signals received by the plurality of transducer units in which the signals are received on a plurality of paths in the object in which the plurality of transducer units is associated with the object; and determine whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays in the time delays for the number of modes in the signals that is greater than a desired amount.

14. The health monitoring system of claim **13**, wherein the signal analysis module is further configured to determine whether an inconsistency is present based on whether the time delay in the time delays for the number of modes in the signals has the difference from the number of other time delays for the number of modes that is greater than the desired amount.

15. The health monitoring system of claim **13**, wherein the signal analysis module is further configured to identify a path in the plurality of paths corresponding to the time delay as having an inconsistency in response to the time delay having the difference that is greater than the desired amount.

16. The health monitoring system of claim **13**, wherein in being configured to identify the time delays for the number of modes in the signals, the signal analysis module is configured to identify velocities for the number of modes in the signals received at the plurality of transducer units, wherein a comparison of the velocities with each other is used to identify the time delays; and wherein in being configured to determine whether the time delay in the time delays for the number of modes in the signals has the difference from the number of other time delays in the time delays for the number of modes in the signals that is greater than the desired amount, the signal analysis module is configured to determine whether a velocity in the velocities for the number of modes in the signals has a difference from other velocities in the velocities that is greater than the desired amount.

17. The health monitoring system of claim **13**, wherein in being configured to determine whether the time delay in the time delays for the number of modes in the signals has the difference from the number of other time delays in the time delays for the number of modes that is greater than the desired amount, the signal analysis module is configured to generate an index value for the number of modes for each path in the plurality of paths to form a plurality of index values, wherein the index value provides an indication of the time delay corresponding to the each path; identify a threshold value, wherein an inconsistency is identified as being present if the index value is greater than the threshold value; compare the index value in the plurality of index values with a threshold; and identify a set of index values that are greater than the threshold.

18. A health monitoring system of an aircraft, the health monitoring system comprising:

a transducer system associated with a number of structures in the aircraft; and

a signal analysis module configured to cause a first plurality of transducer units associated with the number of structures in the aircraft to send signals on a plurality of paths in an object; identify time delays for asymmetric modes in the signals received by a second plurality of transducer units in the transducer system; and determine whether a time delay in the time delays for the asymmetric modes in the signals has a difference from a number of other time delays for the asymmetric modes that is greater than a desired amount.

19. The health monitoring system of claim **18**, wherein the signal analysis module is further configured to extract the asymmetric modes in the signals in which an asymmetric mode in the asymmetric modes is for a corresponding path in the plurality of paths and wherein in being configured to identify the time delays for the asymmetric modes in the signals, the signal analysis module is configured to identify index values for the plurality of paths using the asymmetric mode for the each path in which each index value is for a particular path in the plurality of paths.

20. The health monitoring system of claim **19**, wherein in being configured to determine whether the time delay in the time delays for the asymmetric modes in the signals has the difference from the number of other time delays for the asymmetric modes that is greater than the desired amount, the signal analysis module is further configured to arrange the index values in an ascending order; perform a statistical analysis using the index values in the ascending order; and identify a first index value in the ascending order having a value greater than a threshold, wherein a path corresponding to the first index value and any paths corresponding to any index values greater than the first index value are identified as having an inconsistency.

* * * * *

US008707787B1

(12) United States Patent
Sohn et al.

(10) Patent No.: US 8,707,787 B1
(45) Date of Patent: Apr. 29, 2014

(54) **TIME DELAY BASED HEALTH MONITORING SYSTEM USING A SENSOR NETWORK**

(75) Inventors: **Hoon Sohn**, Seoul (KR); **Chul Min Yeum**, Cheongju (KR); **Jeong-Beom Ihn**, Bellevue, WA (US)

(73) Assignee: **The Boeing Company**, Chicago, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 355 days.

(21) Appl. No.: **13/084,276**

(22) Filed: **Apr. 11, 2011**

Related U.S. Application Data

(60) Provisional application No. 61/449,577, filed on Mar. 4, 2011.

(51) **Int. Cl.**
G01N 29/07 (2006.01)

(52) **U.S. Cl.**
USPC **73/602**; 73/597; 73/620

(58) **Field of Classification Search**
USPC 73/602, 596, 618, 620, 625, 627, 628, 73/633, 597; 702/35, 36, 39, 159
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,431,054 A * 7/1995 Reeves et al. 73/612
5,563,346 A * 10/1996 Bartelt et al. 73/626
6,996,480 B2 * 2/2006 Giurgiutiu et al. 702/35
7,286,964 B2 10/2007 Kim
7,333,898 B2 2/2008 Griess et al.
7,596,470 B2 9/2009 Kim
7,743,659 B2 * 6/2010 Kearns et al. 73/632
7,822,573 B2 10/2010 Ihn
7,881,881 B2 * 2/2011 Giurgiutiu et al. 702/39
7,917,311 B2 * 3/2011 Finkel et al. 702/39
7,921,727 B2 4/2011 Rice
7,991,587 B2 8/2011 Ihn
8,286,490 B2 * 10/2012 Ruzzene et al. 73/618
8,286,492 B2 10/2012 Sohn et al.
2007/0265808 A1 11/2007 Kim
2012/0255359 A1 10/2012 Sohn et al.

FOREIGN PATENT DOCUMENTS

GB 2451959 A 2/2009

OTHER PUBLICATIONS

Petculescu et al., "Group delay measurements using modally selective Lamb wave transduceers for detection and sizing of delaminations in composites", Smart Materials and Structures, 17 (2008) pp. 1-9.
Sohn, "Effects of environmental and operational variability on structural health monitoring", Philosophical Transactions of The Royal Society, 2007, pp. 1-23.

(Continued)

Primary Examiner — J M Saint Surin
(74) *Attorney, Agent, or Firm* — Yee & Associates, P.C.

(57) **ABSTRACT**

A method and apparatus for detecting an inconsistency in an object. Signals sent on a plurality of paths in the object are received at a plurality of transducer units associated with the object. Time delays are identified for a number of modes in the signals received at the plurality of transducer units. A determination is made as to whether a time delay in the time delays for the number of modes in the signals has a difference from a number of other time delays for the number of modes that is greater than a desired amount.

20 Claims, 16 Drawing Sheets