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MECHANICAL EXCITATION FOR ACOUSTIC INTERROGATION OF MATERIALS

Abstract

A system includes an acoustic exciter that is configured to be supported by a platform. The acoustic exciter includes a plurality of excitation elements that rotate about an axis of rotation to cause acoustic excitation of a substrate via contact with the substrate. The acoustic exciter is repositionable relative to the platform to alter an excitation path that is applied to the substrate by the excitation elements. The system further includes a sensor that is configured to sense an acoustic response of the acoustic excitation.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of the filing date of U.S. Provisional Patent Application No. 63/551,383, filed on Feb. 8, 2024, the disclosure of which is incorporated herein by reference.

TECHNICAL FIELD

[0002] This document relates, generally, to continuous and/or semi-continuous acoustic excitation of surfaces for acoustic interrogation of materials.

BACKGROUND

[0003] Reinforced concrete is one of the most important structural components and has influenced civil infrastructure all over the world. Given the volume of reinforced concrete in the world, its deterioration is one of the most pressing global problems and has inspired investigations by scientists and engineers to enable accurate prediction of the deterioration of reinforced concrete. Scientifically validated assessment tools and techniques are needed to enable identification and prioritization of infrastructure rehabilitation projects, especially in scenarios where addressing such challenges may have a political dimension.

[0004] Bridges are vital elements of modern infrastructure. And of all the elements of a bridge, the bridge deck is typically the most susceptible to deterioration, for example due to repeated mechanical loading and exposure to corrosive elements. Not surprisingly, a great deal of attention is placed on inspecting and maintaining bridge decks. However, evaluation and rehabilitation of bridge decks can be particularly challenging because bridge decks are often under traffic, access is limited, and expensive, disruptive traffic control is often necessary. In current practice, bridge evaluation is commonly performed via visual inspection. However, some signs of distress in reinforced concrete structures, such as internal delaminations between layers of concrete, are difficult if not impossible to adequately assess by visual inspection alone.

SUMMARY

[0005] In an aspect, a system may include an acoustic exciter that is configured to be supported by a platform. The acoustic exciter may include a plurality of excitation elements that rotate about an axis of rotation to cause acoustic excitation of a substrate via contact with the substrate. The acoustic exciter may be repositionable relative to the platform to alter an excitation path that is applied to the substrate by the excitation elements. The system may further include a sensor that is configured to sense an acoustic response of the acoustic excitation.

[0006] In another aspect, a system may include an acoustic exciter having a plurality of excitation elements. The acoustic exciter may be configured to maintain substantially continuous contact of the plurality of excitation elements with a substrate. The acoustic exciter may further include a motor that is configured to agitate the plurality of excitation elements to cause acoustic excitation of the substrate. The system may further include a sensor that is oriented to sense an acoustic response of the acoustic excitation.

[0007] In still another aspect, an acoustic exciter may include a plurality of excitation elements that are configured to contact a substrate to cause acoustic excitation in the substrate. The acoustic exciter may further include a head that is configured to support the plurality of excitation elements in a hanging arrangement. The acoustic exciter may further include a shaft having a first end that is coupled to the head and a second end that is spaced from the first end. The shaft may define an axis of rotation of the head. The acoustic exciter may further include a motor that is coupled to the second end of the shaft and configured to rotate the shaft about the axis of rotation. The acoustic exciter may further include a coupler that is configured to mount the motor to a platform such that

the motor is repositionable relative to the platform to vary an angle between the axis of rotation and a surface of the substrate.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0008] FIG. **1** is a block diagram of an example of an acoustic excitation system in accordance with the present disclosure.

[0009] FIG. **2**A is a perspective view of an example acoustic exciter in accordance with the present disclosure.

[0010] FIG. **2**B is a perspective view of the example acoustic exciter illustrated in FIG. **2**A in operation, in accordance with the present disclosure.

[0011] FIG. **3** is a side view of the example acoustic exciter illustrated in FIG. **2**A in operation, with the acoustic exciter repositioned relative to a platform.

[0012] FIG. **4** is a top view of a head that may be implemented in an example acoustic exciter in accordance with the present disclosure.

[0013] FIG. **5**A is a top view of another example acoustic exciter in accordance with the present disclosure.

[0014] FIG. **5**B is a top view of the example acoustic exciter illustrated in FIG. **5**A in operation, in accordance with the present disclosure.

[0015] FIG. **6**A is a block diagram depicting an example arrangement of sensors for an acoustic excitation system in accordance with the present disclosure.

[0016] FIGS. **6**B-**6**C are spectrograms depicting data collected by the sensors during operation of the acoustic excitation system illustrated in FIG. **6**A.

[0017] FIG. **7** is a block diagram depicting another example arrangement of sensors for an acoustic excitation system in accordance with the present disclosure.

[0018] FIG. **8** is a block diagram of another example of an acoustic excitation system in accordance with the present disclosure.

[0019] FIG. **9** is a block diagram the depicts an example of excitation paths applied by acoustic exciters of the acoustic excitation system illustrated in FIG. **8**.

[0020] FIG. **10** is a flow diagram of an example process for operating an acoustic excitation system in accordance with the present disclosure.

[0021] FIG. **11** is a spectrogram from an acoustic excitation interrogation performed using the example process illustrated in FIG. **10**.

DETAILED DESCRIPTION

[0022] The present disclosure relates to one or more acoustic exciters that acoustically excite a substrate. The present subject matter can make use of an ability to automatically perform data analysis of an acoustic response from a material to determine one or more characteristics of the material. In some implementations, it can be determined whether the material has subsurface cracking. For example, this can indicate that a delamination is present in the material.

[0023] A more versatile and continuous excitation of a tested material can be provided. In some implementations, versatility may be enhanced due to one or more exciters having repositionable components and/or due to exciters having compact, highly maneuverable configurations. When one or more excitation elements of an exciter break contact with the surface of a material being interrogated, for example due to rebounding, effectiveness of acoustic measurements may be reduced. In some implementations, one or more exciters are configured such that excitation elements of the exciters maintain substantially continuous contact with the surface of the material. For the purposes of the present disclosure, continuous (e.g., substantially continuous) acoustic excitation refers to a plurality of excitation elements making contact with, for instance impacting, a

material at a frequency such that multiple discrete impacts with the material sound continuous to a human ear but are, in fact, individual impacts. In some implementations, the material being impacted may be a substrate, such as reinforce concrete.
[0024] Known acoustic exciters may lack the ability to perform acoustic excitation within confined spaces, which may make them unsuitable for interrogating materials in such spaces, such as decks within a parking structure, for example. An advantage of an exciter having a compact, highly maneuverable configuration may be the ability to conduct material interrogations within confined spaces, to conduct interrogation of material surfaces not at ground level (e.g., walls, ceilings), and so on.
[0025] Considering the many defects that occur within bridge decks, internal cracking known as delamination is a serious defect. In regions that experience routine application of deicing salts and in coastal regions, chlorides accumulate around the reinforcing steel in the bridge deck, causing rust. As the steel rusts, it expands, producing internal cracks within the concrete. Eventually the concrete spalls, and a pothole is formed. Significant rehabilitation is then necessary to restore reinforced concrete that has reached this advanced stage of deterioration. However, the earlier that detection of defects occurs, the more cost-effective and life-extending the rehabilitation of the bridge deck can be. It should be appreciated that applications of the apparatuses, systems, and methods described herein are not limited to bridge decks. Any concrete or other material made of homogenous or heterogeneous materials with the propensity to crack or disband, such as parking structures, roofs, dams, runways, etc. are within the scope of possible applications.
[0026] When an acoustic exciter acoustically excites a substrate, an acoustic response can be generated by the substrate. Such an acoustic response can be captured by one or more sensors (e.g., a microphone) and can be stored as an analog and/or digital signal. One or more processing techniques can be applied to the data of such a signal.
[0027] FIG. **1** is a block diagram of an example of an acoustic excitation system **100**. The acoustic excitation system **100** may be generally referred to as a system. In some implementations, the acoustic excitation system **100** may include one or more exciters **102**, one or more sensors **104**, one or more analysis components **106**, one or more location components **108**, and a platform **110** to which one or more other components of the acoustic excitation system **100** may be mounted, in one or more combinations. As described herein, one or more components of the acoustic excitation system **100** can interact or otherwise cooperate with each other to perform acoustic excitation and record and analyze acoustic responses thereof.
[0028] As shown, the acoustic excitation system **100** includes a single exciter **102**. The exciter **102** may be configured to cause acoustic excitation of a substrate, such as a portion of a reinforced concrete structure (e.g., a road), for example. The exciter **102** may be configured for manual excitation of the substrate, automatic excitation of the substrate, or a combination thereof.
[0029] The exciter **102** may include one or more components that make contact with the substrate to cause acoustic excitation within the substrate. For example, as shown the exciter **102** may include one or more excitation elements **112**, such as a plurality of excitation elements **112**. The excitation elements **112** may include any acoustic exciter, impactor and/or contact that may be moved (e.g., agitated) to trigger acoustic excitation in at least part of a material. The exciter **102** may be configured to maintain contact of at least one or more of the excitation elements **112** with the substrate during operation.
[0030] The one or more sensors **104** may be configured to sense an acoustic response of the acoustic excitation caused by the excitation elements **112**. In some implementations, the one or more sensors **104** may be implemented as microphones (e.g., directional microphones). In some implementations, the one or more sensors **104** may be mounted such that they are located near the floor or ground so that they pick up impact responses from the material that is being interrogated. The microphones may be placed close to respective contact locations of the excitation elements **112** on a substrate, so that the sensing of ambient noise is mitigated relative to the acoustic response

caused by acoustic excitation. In some implementations, the acoustic excitation system **100** may be configured as a multi-channel system that includes two or more sensors **104**.

[0031] The one or more analysis components **106** may be configured to determine at least one characteristic of the substrate (e.g., the roadway or other material), for example using information related to the sensed acoustic response. In some implementations, the one or more analysis components **106** can include software, firmware, and/or hardware, in any combination. For example, in an example implementation, the one or more analysis components **106** may include circuitry that is configured to determine at least one characteristic of a substrate based on the acoustic response. In some implementations, the one or more analysis components **106** may be configured to receive and/or store signals from the one or more sensors **104** and to process the signals to determine characteristics of the substrate. To illustrate, the one or more analysis components **106** may be configured to perform analysis on data and/or information related to sensed acoustic response to determine whether one or more portions of a substrate contain delaminations.

[0032] The one or more location components **108** may include a positioning system. In some implementations, such a positioning system may include one or more location detectors. For example, positioning in the example implementations described herein may include, but are not limited to, use of differential global positioning system (DGPS) and/or light detection and ranging (LiDAR). Positioning can be achieved by many different methods including global positioning system (GPS), DGPS, real time kinematics GPS (RTK-GPS), odometry, computer vision, optics, radar, LiDAR, beacons, and/or a variety of other techniques, including computed telemetry in post-processing and simultaneous localization and mapping (SLAM) methods that can generate position data and/or generate maps as data are collected. These methods can be used to obtain the position information necessary to be able to generate maps either in real time or in post-processing conditions, for example.

[0033] The platform **110** may be configured to support one or more other components of the acoustic excitation system **100** during acoustic of a substrate. The platform **110** may be configured to remain in a static position and/or may be configured to be movable during operation of the acoustic excitation system **100**. In some implementations, the platform **110** may be provided as a wheeled and/or tracked vehicle, such as a cart for example. The platform **110** may be configured to moved manually or may be configured for self-propelled movement, in any combination. In self-propelled implementations, the platform **110** may be configured to move in response to operator input, to move semi-autonomously, or to move autonomously, in any combination.

[0034] The one or more location components **108** may be configured to identify when the platform **110** is located at an area to be interrogated (e.g., when the platform **110** is traversing or about to traverse a portion of a bridge deck). In some implementations, the one or more location components **108** can be configured to correlate acoustic responses with the structure or surface being acoustically excited. For example, when acoustic response data indicates a possible delamination, data from the one or more location components **108** can be used to determine where on the measured substrate or object the delamination is located.

[0035] FIG. **2**A is a perspective view of an example acoustic exciter **200**. The acoustic exciter **200** may be implemented, for example, as the exciter **102** of the acoustic excitation system **100**. In some implementations, the acoustic exciter **200** includes a head **202**, a motor **204**, a shaft **206** that couples the head **202** to the motor **204**, and one or more excitation elements **208**. As shown, the acoustic exciter **200** includes a plurality of excitation elements **208**. The excitation elements **208** may be configured to contact a substrate **210** to cause acoustic excitation in the substrate **210**.

[0036] In some implementations, the shaft **206** may have a first end **212** that is configured to be coupled to the head **202** and a second end **214** that is spaced from the first end **212**. The second end **214** of the shaft **206** may be coupled to the motor **204**. In some implementations, the second end **214** may be configured to be received in a chuck of the motor **204**. In some implementations, the shaft **206** may be an integrated component of the motor **204**.

[0037] The shaft **206** may define an axis of rotation AR of the head **202**. For example, as shown the axis of rotation AR extends coaxially with a longitudinal axis of the shaft **206**. The motor **204** is configured to rotate the shaft **206**, and thus the head **202**, about the axis of rotation AR.

[0038] In some implementations, the head **202** may be configured to support the plurality of excitation elements **208**. For example, as shown the head **202** is configured to support the plurality of excitation elements **208** in a hanging arrangement. In some implementations, the head **202** may include one or more attachment locations **216** that are configured to enable attachment of the plurality of excitation elements **208** to the head **202**. As shown, the head **202** is disc-shaped and includes four attachment locations **216** that are spaced apart from one another around a circumference of the head **202**.

[0039] One or more of the attachment locations **216** may be configured to allow a portion of the plurality of excitation elements **208** to be attached to, and thereby suspended from, the head **202**. For example, in an example implementation, each attachment location **216** may comprise an aperture configured to receive a fastener for connecting a portion of the plurality of excitation elements **208**. In another example implementation, each attachment location **216** may include a ring-shaped structure that is attached to an underside of the head **202**, such as an eyebolt, a carabiner clip, or the like.

[0040] In some implementations, acoustic exciter **200** may include one or more connecting elements **218** that enable attachment of the plurality of excitation elements **208** to the attachment locations **216**. In some implementations, the connecting elements **218** may be configured to provide a non-rigid attachment between respective ones of the excitation elements **208** and the attachment locations **216**, for instance such that an excitation element **208** is able to move freely while connected to an attachment location **216**. In some implementation, the connecting elements **218** may be provided as carabiners, bolt snaps, split rings, loops of wire, loops of string, and so on. As shown, the acoustic exciter **200** may include one or more connecting elements **218** in the form of one or more carabiners at each attachment location **216** that attach the plurality of excitation elements **208** to the head **202** in a dangling arrangement. As shown, the acoustic exciter **200** may include one or more carabiners, connected to each other, at each attachment location **216**. In some implementations, the acoustic exciter **200** may include more or fewer connecting elements **218**, such as more or fewer carabiners. For example, in some implementations the acoustic exciter **200** may include no connecting elements, such that portions of the plurality of excitation elements **208** may be connected directly to respective ones of the attachment locations **216**.

[0041] In some implementations, the excitation elements **208** may include a plurality of interconnected links **220**, such as chain links. For example, in some implementations, the excitation elements **208** may be provided as one more lengths of chain **222**. Chains **222** may provide multiple interactions across the surface of a substrate because they include many contact elements flexibly coupled together. Furthermore, the contact events they produce are inherently stochastic because one or more of spacing, contact duration, and timing may change as the excitation elements **208** are rotated. Other excitation elements, such as beads, rods, or balls on wires, for example, could be implemented in place of chain **222**, but may not be preferred.

[0042] As shown, the plurality of excitation elements **208** is provided as a length of chain **222** that is connected at its loose ends by a quick link. As shown, the chain **222** is connected to the head **202** via carabiners at each attachment location **216**, such that the chain **222** is divided into four segments of approximately the same length. In some implementations, the chain **222** may be provided in a length that exceeds the circumference of the head **202**, such that each segment of the chain **222**, for example as defined between adjacent attachment locations **216**, hangs in a sagging manner. In this regard, the head **202** may be configured such that when the plurality of interconnected links **220** (e.g., the chain **222**) is suspended from the plurality of attachment locations **216**, respective segments of the plurality of interconnected links **220** exhibit sag between adjacent ones of the plurality of attachment locations **216**.

[0043] In some implementations, the acoustic exciter **200** may include a coupler **224** that is configured to mount the motor **204** to a platform **226** (e.g., such as the platform **110** of the acoustic excitation system **100**). The coupler **224** may be configured to enable repositioning of the motor **204** relative to the platform **226** in multiple degrees of freedom. For example, the coupler **224** may be configured such that the motor **204** is repositionable relative to the platform **226** to vary an angle between the axis of rotation AR and a surface of the substrate **210**. For example, in some implementations, the coupler **224** may be configured to enable repositioning of the motor **204** such that the axis of rotation AR pivots about the coupler **224** in one or both of a longitudinal direction LO and a lateral direction LA. In some implementations, the coupler **224** may be configured for manual repositioning of the motor **204**. For example, in such an implementation the coupler **224** may be provided as a ball head coupler or the like. In some implementations, the coupler **224** may be configured to automatic (e.g., actuator controlled) repositioning of the motor **204**. For example, in such an implementation the coupler **224** may be provided as a multi-axis positioner.

[0044] FIG. **2**B is a perspective view of the acoustic exciter **200** in operation. In some implementations, the motor **204** may be configured to agitate the plurality of excitation elements **208** to cause acoustic excitation. For example, as shown the motor **204** may be configured to drive rotation of the shaft **206**, and thus the head **202**, about the axis of rotation AR such that the plurality of excitation elements **208** make and maintain contact with the substrate **210**.

[0045] In some implementations, the acoustic exciter **200** may be configured such that the motor **204** rotates the head **202** at a rotational speed that causes the plurality of excitation elements **208** to move in a predictable manner such that the excitation elements form an excitation path relative to the substrate **210**. For example, as shown the motor **204** may be configured to rotate the head **202** at a rotational speed that causes the chain **222** to move in a substantially circular excitation path, wherein adjacent interconnected links **220** generally follow one another along the excitation path. This may result in an excitation path having a narrow, annular shape.

[0046] As shown, the motor **204** may be positioned, for example via the coupler **224**, such that the axis of rotation AR is substantially orthogonal relative to a planar surface of the substrate **210**. As the motor **204** rotates the head **202** about the axis of rotation AR, the excitation path may remain substantially circular and the plurality of excitation elements **208** may maintain substantially continuous contact with the surface of the substrate **210**. In this regard, the acoustic exciter **200** may be configured to maintain substantially continuous contact of the plurality of excitation elements **208** with the substrate **210**.

[0047] In some implementations, the motor **204** may be selected and/or configured to enhance the likelihood that the plurality of excitation elements **208** maintain substantially continuous contact with the surface of the substrate **210**. For example, the speed at which the motor **204** rotates the head **202** may introduce radial forces that are not found in linear arrangements of excitation elements **208**. At high enough speeds, one or more of the excitation elements **208** may change their vertical distance to the surface. A threshold torque may need to be applied by the motor **204** before the excitation elements **208** will initially begin to rotate along the surface of the substrate **210**. However, as the speed of rotation increases and one or more excitation elements **208** bounce off of the surface, the excitation elements **208** may reduce the overall interfacial friction. Reducing the overall interfacial friction may then increase the speed of rotation of the head **202**, which in turn may result in fewer interactions with the surface of the substrate **210**. Eventually, the rotational speed may increase to a point that substantially all of the excitation elements may leave the surface and simply rotate in the air above the substrate **210**.

[0048] To reduce the likelihood of such a situation, the acoustic exciter **200** may be provided with a motor **204** having a geared system with substantial torque at low speeds and/or with a feedback system to limit the maximum rotation speed of the excitation elements **208** in response to reduced friction with the surface of the substrate **210**. This may produce a continuous, high torque rotation.

To illustrate, based on gearing of the motor **204**, significant torque may be applied initially, resulting in the excitation elements **208** maintaining contact with the substrate **210**. A geared system with substantial torque at low speeds or a rotation speed feedback system may operate to limit a maximum rotation speed of the plurality of excitation elements **208** in response to situations with reduced friction with the substrate **210** in order to maintain contact with the surface of the substrate **210** during an interrogation.

[0049] The motor **204** may be provided as an electric motor, as a gas-powered motor, or as another source of power that is capable of rotating the head **202** about the axis of rotation AR. In a preferred implementation, the head **202** may be mechanically coupled to a motor **204** (e.g., an electrical motor) that can provide the force necessary to move the excitation elements **208** along a continuous path that may be circular, ellipsoidal, or another shape and/or also somewhat determined by the speed and collisions of the excitation elements **208** with the surface.

[0050] The rotational speed at which the motor **204** drives rotation of the head **202** may be based on a speed at which the platform **226** traverses the substrate **210**. For example, the acoustic exciter **200** may be configured such that the motor **204** may increase or decrease the rotational speed of the head **202** proportionally with movement speed of the platform **226**. To illustrate, the motor **204** may reduce rotational speed of the head **202** as the movement speed of the platform **226** slows but continues to provide excitation once the platform **226** is completely stopped.

[0051] In some implementations, the acoustic exciter **200** may be configured such that the motor **204** counter-rotates the head **202** relative to the direction of movement of the platform **226** in order to speed up the movement of the excitation elements **208** relative to the surface of the substrate **210** to be interrogated. In some implementations, the acoustic exciter **200** be configured to rotate the head **202** in the direction relative to the movement of the platform **226** to slow down movement of excitation elements **208** relative to the surface of the substrate **210** to be interrogated, thus allowing operation of the acoustic exciter **200** at higher speeds by slowing down the relative speed of impacts.

[0052] Feedback related to acoustic signals or position of the excitation elements **208** may be used to control the rotational speed at which the head **202** is driven by the motor **204** to adjust for the intensity of impacts and the speed of the excitation elements **208** relative to the surface of the substrate **210**.

[0053] In some implementations, the acoustic exciter **200** may be configured such that the motor **204** periodically reverses the direction of rotation of the head **202** about the axis of rotation AR. For example, the acoustic exciter **200** may be configured such that the motor rotates the head **202** in a clockwise direction for a first interval of time, rotates the head **202** in a counter-clockwise direction for a second interval of time, rotates the head **202** in a clockwise direction for a third interval of time, and so on. This pattern of changing the direction of rotation of the head **202** may be designed such the plurality of excitation elements **208** can impart sufficient energy into the surface of the substrate **210** but not spin so fast that excitation elements **208**, such as those along the edges of the excitation path for instance, leave the surface of the substrate **210** to be interrogated. In some implementations, this may cause the excitation elements **208** to generate an S-shaped (e.g., snake-like) motion along the length of the chain **222**.

[0054] In some implementation, constant rotational speed of the head **202** may be preferred over the delivery of constant power by the motor **204**. Under a constant power delivery scenario, it was observed that, if friction is reduced substantially between the excitation elements **208** and the surface of the substrate **210**, the spinning motion may accelerate further, which may lift more excitation elements **208** from the surface of the substrate **210**, for instance to the point that substantially all of the excitation elements **208** may leave the surface simultaneously. Accordingly, adjusting the rotation speed imparted to the head **202** by the motor **204** to maintain substantially continuous contact between the excitation elements **208** and the surface of the substrate **210** is preferred. This principle was verified in multiple experiments with different implementations of the acoustic exciter **200**.

[0055] FIG. **3** is a side view of the acoustic exciter **200** in operation, with the acoustic exciter **200** repositioned relative to the platform **226**. In some implementations, the motor **204** may be repositioned relative to the platform **226** via the coupler **224**, such that an angle α between the axis of rotation AR a surface of the substrate **210** changes. To illustrate, the motor **204** may be repositioned from a first position in which the axis of rotation AR is substantially orthogonal relative to the surface of the substrate **210** such that α˜90° (e.g., as shown in FIGS. **2**A-**2**B) to a second position in which α<90° as shown.

[0056] As shown, the acoustic exciter **200**, and in particular the motor **204**, may be repositioned such that the motor **204** is tilted rearward in the longitudinal direction LO, relative to a direction of travel DT of the platform **226** along the substrate **210**. With the acoustic exciter **200** repositioned as shown, a quantity of the plurality of excitation elements **208** that simultaneously make contact with the substrate **210** is reduced. Stated differently, repositioning the acoustic exciter **200** relative to the platform **226** may result in varying the quantity of the plurality of excitation elements **208** that simultaneously make contact with the substrate **210**.

[0057] In some implementations, reducing the quantity of the plurality of excitation elements **208** that simultaneously make contact with the substrate **210** may alter the excitation path that is applied to the substrate **210** by the excitation elements **208**. For example, with the acoustic exciter **200** repositioned as shown, the excitation path applied to the substrate **210** by the excitation elements **208** will be arc shaped.

[0058] FIG. **4** is a perspective view of an example head **402** that may be implemented in an acoustic exciter. For instance, in some implementations the head **402** may be implemented in place of the head **202** in the acoustic exciter **200** (e.g., attached to the first end **212** of the shaft **206**). As shown, the head **402** includes a first bar **404** and a second bar **406** that are attached to one another in a cross configuration. In some implementations, the head **402** may include one or more attachment locations **416** that are configured to enable attachment of the plurality of excitation elements **208** to the head **402**. For example, as shown the head **402** includes four attachment locations **416**, including two at opposed ends of the first bar **404** and two at opposed ends of the second bar **406**.

[0059] FIGS. **5**A and **5**B are top views of another example acoustic exciter **500**. The acoustic exciter **500** may be implemented, for example, as the exciter **102** of the acoustic excitation system **100**. In some implementations, the acoustic exciter **500** includes a head **502**, a motor **504**, and one or more excitation elements **508**. As shown, the acoustic exciter **500** includes a plurality of excitation elements **508**. The excitation elements **508** may be configured to contact a substrate **210** to cause acoustic excitation in the substrate **210**. Although not shown, the acoustic exciter **500** may include a shaft that couples the head **502** to the motor **504** and a coupler that is configured to mount the motor **504** to a platform (e.g., such as the platform **110** of the acoustic excitation system **100**).

[0060] In some implementations, the plurality of excitation elements **508** may comprise separate two or more separate portions of excitation elements **508** that are supported by the head **502**. For example, as shown the plurality of excitation elements **508** comprises a first segment **510** of excitation elements **508** and a second segment **512** of excitation elements **508** that is separate from the first segment **510**.

[0061] As shown, the head **502** is disc-shaped and includes two attachment locations **516** that are spaced apart from one another around a circumference of the head **502**. More specifically, the head **502** includes a first attachment location **516** that is configured to support the first segment **510** of the plurality of excitation elements **508** and a second attachment location **516** that is configured to support the second segment **512** of the plurality of excitation elements **508**.

[0062] In some implementations, the acoustic exciter **500** may be configured such that the motor **504** rotates the head **502** at a rotational speed that causes the first segment **510** and the second segment **512** of the plurality of excitation elements **508** to move in a substantially circular excitation path, wherein adjacent interconnected links **220** generally follow one another along the excitation path. This may result in an excitation path having an annular shape, which may be wider than the excitation path formed by the excitation elements **208** of the acoustic exciter **200**.

[0063] FIG. **6**A is a block diagram depicting an example acoustic excitation system **600** in accordance with the present disclosure. The acoustic excitation system **600** may be implemented, for example, as the acoustic excitation system **100**. In some implementations, the acoustic excitation system **600** may include an acoustic exciter **602** and one or more sensors **604**. For example, as shown the acoustic excitation system **600** includes two sensors **604**, including a first sensor **604***a* and a second sensor **604***b*.

[0064] In some implementations, the sensors **604** may be provided as microphones (e.g., microphones with directional gain). Such microphones may be used to sense possible defects at multiple points along a path of excitation of the acoustic excitation system **600**. This may provide additional spatial information obtained along the path of excitation, for example when compared with known interrogation techniques.

[0065] As shown, the acoustic exciter **602** may include a plurality of excitation elements **608** that form an oval-shaped excitation path **630** along a surface of the substrate **210** during operation of the acoustic excitation system **600**.

[0066] As shown, the acoustic excitation system **600** is configured such that the first sensor **604***a* is oriented to sense a first acoustic response **632** caused at a first location **634** along the excitation path **630** by the plurality of excitation elements **608**, and such that the second sensor **604***b* is oriented to sense a second acoustic response **636** caused at a second location **638** along the excitation path **630** by the plurality of excitation elements **608**.

[0067] In some implementations, the acoustic excitation system **600** may include one or more analysis components that are configured to determine at least one characteristic of the substrate **210** (e.g., the roadway or other material), for example using information related to the sensed first acoustic response **632** and the sensed second acoustic response **636**. The one or more analysis components may be implemented in accordance with the one or more analysis components **106** of the acoustic excitation system **100**, for example. In accordance with the illustrated implementation, the one or more analysis components may include circuitry configured to determine at least one characteristic of the substrate **210** based on the first acoustic response **632** and the second acoustic response **636**.

[0068] An advantage of having an acoustic excitation system that maintains substantially continuous impacts of its excitation elements, such as the acoustic excitation system **600**, for example, is that a path of interrogation of such an acoustic excitation system may cover more area of a substrate than may be covered by other known interrogation systems, such as those that employ point impacts, for example. Data from multiple sensors may be collected along a path of interrogation.

[0069] To illustrate, FIGS. **6**B and **6**C are spectrograms that depict example results based on acoustic data collected by the first sensor **604***a* and the second sensor **604***b* during interrogation of the substrate **210** by the acoustic excitation system **600**. The acoustic data was analyzed as shown in FIGS. **6**B and **6**C, illustrating how employing multiple sensors **604**, such the first sensor **604***a* and the second sensor **604***b* can pick up different defect information along an interrogation path.

[0070] In accordance with the illustrated results, the excitation elements **608** may produce broadband acoustic excitation that is particularly notable in the frequency region between 15 and 20 kHz. It should be noted that first the impacts between 15 and 25 seconds appear stronger on the first sensor **604***a* and then the impacts between 25 and 35 seconds appear stronger on the second sensor **604***b*. This may indicate that spatial source separation is possible along a single continuous excitation path of the excitation elements **608** as the acoustic excitation system **600** traverses the substrate **210**. The illustrated results are based on a configuration in which a platform to which the acoustic excitation system **600** is mounted remains stationary, thereby demonstrating the utility of active mechanical rotations of the excitation elements **608** for interrogation at low speeds and/or when the acoustic excitation system **600** in not moving.

[0071] As shown, the first sensor **604***a* and the second sensor **604***b* may be provided as respective first and second microphones, each microphone having directional acoustic patterns, may be directed towards different points (e.g., the first location **634** and the second location **638**) of the continuous excitation along the surface of the substrate **210**. In some implementations, the first sensor **604***a* and the second sensor **604***b* may be connected to a multichannel amplifier and digitizer. Acoustic signals may be recorded, for example by a computer running sound software in which multiple channels of acoustic data are recorded simultaneously.

[0072] In some implementation, the acoustic excitation system **600** may include a platform to which the acoustic exciter **602** and the sensors **604** are mounted. In such an implementation, a platform may enable movement of the excitation elements **608**, for example in the longitudinal direction LO, the latitudinal direction LA, or a combination thereof. The acoustic excitation system **600** may be configured to enable adjustment of a height of the excitation elements **608** (e.g., vertically) relative to the surface of the substrate **210** to be interrogated. In some implementations, the sensors **604** may be mounted to the platform such that respective orientations of the sensors **604** are maintained relative to the excitation elements **608**.

[0073] It should be appreciated that acoustic excitation systems may be implemented with any number of acoustic exciters and/or sensors, for example in accordance with characteristics of the substrate **210** which is to be interrogated. For example, FIG. **7** is a block diagram depicting an example acoustic excitation system **700**. The acoustic excitation system **700** may be implemented, for example, as the acoustic excitation system **100**.

[0074] In some implementations, the acoustic excitation system **700** may include an acoustic exciter **702** and one or more sensors **704**. For example, as shown the acoustic excitation system **700** includes four sensors **604**, including a first sensor **704***a*, a second sensor **704***b*, a third sensor **704***c*, and a fourth sensor **604***d*.

[0075] In some implementations, the sensors **604** may be provided as microphones (e.g., microphones with directional gain). Such microphones may be used to sense possible defects at multiple points along a path of excitation of the acoustic excitation system **700**.

[0076] As shown, the acoustic exciter **702** may include a plurality of excitation elements **708** that form an oval-shaped excitation path **730** along a surface of the substrate **210** during operation of the acoustic excitation system **700**.

[0077] As shown, the acoustic excitation system **700** is configured such that the first sensor **704***a* is oriented to sense a first acoustic response **732** caused at a first location **734** along the excitation path **730** by the plurality of excitation elements **708**, such that the second sensor **704***b* is oriented to sense a second acoustic response **736** caused at a second location **738** along the excitation path **730** by the plurality of excitation elements **708**, such that the third sensor **704***c* is oriented to sense a third acoustic response **740** caused at a third location **742** along the excitation path **730** by the plurality of excitation elements **708**, and such that the fourth sensor **704***d* is oriented to sense a fourth acoustic response **746** caused at a fourth location **748** along the excitation path **730** by the plurality of excitation elements **708**.

[0078] In some implementations, the acoustic excitation system **700** may include one or more analysis components that are configured to determine at least one characteristic of the substrate **210** (e.g., the roadway or other material), for example using information related to the sensed first acoustic response **732**, the sensed second acoustic response **736**, the sensed third acoustic response **740**, and the sensed fourth acoustic response **746**. The one or more analysis components may be implemented in accordance with the one or more analysis components **106** of the acoustic excitation system **100**, for example. In accordance with the illustrated implementation, the one or more analysis components may include circuitry configured to determine at least one characteristic of the substrate **210** based on the first acoustic response **732**, the second acoustic response **736**, the third acoustic response **740**, and the fourth acoustic response **746**.

[0079] FIG. **8** is a block diagram depicting an example acoustic excitation system **800**. The acoustic excitation system **800** may be implemented, for example, as the acoustic excitation system **100**.

[0080] In some implementations, the acoustic excitation system **800** may include two or more acoustic exciters. For example, as shown the acoustic excitation system **800** may include a first acoustic exciter **802**, a second acoustic exciter **804**, and a third acoustic exciter **806**. The first acoustic exciter **802**, the second acoustic exciter **804**, and the third acoustic exciter **806** may be implemented in accordance with any of the example acoustic exciters described herein, such as the acoustic exciter **200** for example.

[0081] In accordance with the illustrated implementation, the first acoustic exciter **802** may include a first plurality of excitation elements **808***a* that form an oval-shaped first excitation path **830** along a surface of the substrate **210**. The first acoustic exciter **802** may include a first motor **810** that is configured to agitate the first plurality of excitation elements **808***a* (e.g., via rotating the excitation elements **808***a* about an axis of rotation AR of the first motor **810**) to cause acoustic excitation of the substrate **210**.

[0082] Additionally, the second acoustic exciter **804** may include a second plurality of excitation elements **808***b* that form an oval-shaped second excitation path **832** along the surface of the substrate **210**. The second acoustic exciter **804** may include a second motor **812** that is configured to agitate the second plurality of excitation elements **808***b* (e.g., via rotating the excitation elements **808***b* about an axis of rotation AR of the second motor **812**) to cause acoustic excitation of the substrate **210**.

[0083] Furthermore, the third acoustic exciter **806** may include a third plurality of excitation elements **808***c* that form an oval-shaped third excitation path **834** along the surface of the substrate **210**. The third acoustic exciter **806** may include a third motor **814** that is configured to agitate the third plurality of excitation elements **808***c* (e.g., via rotating the excitation elements **808***c* about an axis of rotation AR of the third motor **814**) to cause acoustic excitation of the substrate **210**.

[0084] In some implementations, each of the first acoustic exciter **802**, the second acoustic exciter **804**, and the third acoustic exciter **806** may include one or more sensors. For example, as shown the first acoustic exciter **802** may include a first sensor **816** that is oriented to sense a first acoustic response associated with (e.g., caused by) the first plurality of excitation elements **808***a*, the second acoustic exciter **804** may include a second sensor **818** that is oriented to sense a second acoustic response associated with (e.g., caused by) the second plurality of excitation elements **808***b*, and the third acoustic exciter **806** may include a third sensor **820** that is oriented to sense a third acoustic response associated with (e.g., caused by) the third plurality of excitation elements **808***c*.

[0085] In some implementations, the acoustic excitation system **800** may include one or more analysis components that are configured to determine at least one characteristic of the substrate **210** (e.g., the roadway or other material), for example using information related to the first acoustic response sensed by the first sensor **816**, the second acoustic response sensed by the second sensor **818**, and the third acoustic response sensed by the third sensor **820**. The one or more analysis components may be implemented in accordance with the one or more analysis components **106** of the acoustic excitation system **100**, for example. In accordance with the illustrated implementation, the one or more analysis components may include circuitry configured to determine at least one characteristic of the substrate **210** based on the first acoustic response, the second acoustic response, and the third acoustic response.

[0086] In some implementations, the acoustic excitation system **800** may include a platform **826** to which the first acoustic exciter **802**, the second acoustic exciter **804**, and the third acoustic exciter **806** are mounted, for example via respective couplers (e.g., such as the coupler **224** of the acoustic exciter **200**). In some implementations, the platform **826** may be configured to traverse the substrate **210** along a direction of travel DT. In some implementations, the first sensor **816**, the second sensor **818**, and the third sensor **820** may be attached to the platform **826**.

[0087] As shown, each of the first acoustic exciter **802**, the second acoustic exciter **804**, and the third acoustic exciter **806** may be positioned such that the axes of rotation AR of the first motor **810**, the second motor **812**, and the third motor **814**, respectively, are aligned substantially orthogonally with a surface of the substrate **210**. In accordance with this configuration, the first acoustic exciter **802** may be configured to maintain substantially continuous contact of the first plurality of excitation elements **808***a* with the substrate **210**, the second acoustic exciter **804** may be configured to maintain substantially continuous contact of the second plurality of excitation elements **808***b* with the substrate **210**, and the third acoustic exciter **806** may be configured to maintain substantially continuous contact of the third plurality of excitation elements **808***c* with the substrate **210**.

[0088] In accordance with the illustrated configuration of the acoustic excitation system **800**, the first acoustic exciter **802** may be mounted to the platform **826** at a first location **836** such that it causes acoustic excitation of the substrate **210** in a first area A**1** defined by the first excitation path **830**, the second acoustic exciter **804** may be mounted to the platform **826** at a second location **838** such that it causes acoustic excitation of the substrate **210** in a second area A**2** defined by the second excitation path **832**, and the third acoustic exciter **806** may be mounted to the platform **826** at a third location **840** such that it causes acoustic excitation of the substrate **210** in a third area A**3** defined by the third excitation path **834**.

[0089] As shown, the first location **836** may be aligned with the third location **840** along the longitudinal direction LO and the second location **838** may be spaced from the first location **836** and the third location **840** along the longitudinal direction LO. Additionally, the first location **836** may be spaced from the third location **840** along the lateral direction LA, and the second location **838** may be spaced from the first location **836** and the third location **840** along the lateral direction LA, for example such that the second location **838** is located equidistantly from the first location **836** and the third location **840** along the lateral direction LA.

[0090] In some implementations, the first location **836**, the second location **838**, and the third location **840** may be configured such that respective paths of interrogation of the first acoustic exciter **802**, the second acoustic exciter **804**, and the third acoustic exciter **806** at least partially overlap, for example as the platform **826** traverses the substrate **210** along the direction of travel DT and the acoustic excitation system **800** interrogates the substrate **210**. For example, as shown the second location **838** may be spaced from the first location **836** (e.g., along one or both of the longitudinal direction LO and the lateral direction LA) such that the second area A**2** at least partially overlaps the first area A**1**, and third location **840** may be spaced from the second location **838** (e.g., along one or both of the longitudinal direction LO and the lateral direction LA) such that the third area A**3** at least partially overlaps the second area A**2**.

[0091] FIG. **9** is a block diagram illustrating an example of operation of the acoustic excitation system **800** interrogating the substrate **210**. As shown, the first acoustic exciter **802**, the second acoustic exciter **804**, and the third acoustic exciter **806** may be repositioned such the respective axes of rotation AR are no longer orthogonal relative to the surface of the substrate **210**. This may result in the first excitation path **830**, the second excitation path **832**, and the third excitation path **834** forming arc-shaped geometries of contact with the substrate **210**. As shown, as the platform **826** traverses the substrate **210** along the direction of travel DT, the coverage of the first area A**1**, the second area A**2**, and the third area A**3** may partially overlap one another, creating bands B**1** and B**2** of overlapping coverage.

[0092] FIG. **10** is a flow diagram of an example process **1000** for operating an acoustic excitation system. The process **1000** may be implemented with any acoustic excitation system implemented in accordance with the instant disclosure, for example one or more of the acoustic excitation system **100**, the acoustic excitation system **600**, the acoustic excitation system **700**, or the acoustic excitation system **800**.

[0093] In an example implementation, the process **1000** may be utilized in a scenario in which the acoustic exciters of an acoustic excitation system are activated to drive respective excitation elements before a platform on which components of the acoustic excitation system are mounted enters an area to interrogated.
[0094] At step **1002**, an interrogation area of a substrate (e.g., the substrate **210**) may be determined.
[0095] At step **1004**, the acoustic exciters of the acoustic excitation system may be activated to drive respective excitation elements, for example by rotating respective pluralities of excitation elements about respective axes of rotation of the acoustic exciters. Optionally at step **1004**, one or more acoustic exciters of the acoustic excitation system may be repositioned (e.g., as described elsewhere herein), which may cause reconfiguration of the respective excitation paths of one or more of the pluralities of excitation elements.
[0096] At step **1006**, a platform upon which the acoustic exciters are mounted may be controlled to move into the interrogation area.
[0097] At step **1008** the platform may advance within the interrogation area along a direction of travel, with the acoustic exciters providing acoustic excitation in the substrate by maintaining substantially continuous contact of the pluralities of excitation elements with the surface of the substrate. As the platform traverses through the interrogation area, data may be collected. For example, one or more sensors of the acoustic excitation system may sense acoustic responses in the substrate caused by the acoustic excitation provided by the pluralities of excitation elements.
[0098] One or more aspects, such as all aspects, of the data collection of may be automated, including but not limited to repositioning one or more of the acoustic exciters during interrogation, varying rotational speed of one or more of the pluralities of excitation elements, and the starting and/or stopping of data collection. The automated system can perform these tasks based on the estimated position of the platform (e.g., in the longitudinal direction LO or the lateral direction LA), for example, by causing the one or more acoustic exciters to initiate agitation of the pluralities of excitation elements as the platform approaches the interrogation area, collecting acoustic response data while the platform traverses the interrogation area, and ceasing data collection and/or causing agitation of the pluralities of excitation elements to be ceased as the platform leaves the interrogation area.
[0099] In some implementations, the acoustic excitation system may be configured to determine whether a portion of the interrogation area (e.g., a lane of a bridge) needs to be scanned or if it has already been scanned and control components of the system accordingly. If the system is operated in this fashion, a single operator can accomplish all tasks because all of the data collection aspects can be controlled by a computer. The operator can simply make sure the platform is positioned properly within the interrogation area during traversal of the platform while the acoustic excitation system performs its functions.
[0100] Furthermore, in some implementations the acoustic excitation system may be configured to operate in a fully autonomous manner, for example to carry out scanning in a pre-determined interrogation area, without any intervention by an operator.
[0101] At step **1010**, the platform may reach the end of the interrogation area.
[0102] At step **1012**, upon the platform leaving the interrogation area, the one or more acoustic exciters of the acoustic excitation system may be controlled to cease agitation of the pluralities of excitation elements.
[0103] At step **1014**, acoustic response data acquired during acoustic excitation in the interrogation area may be processed. In some implementations, the data may be processed into one or more maps of the interrogation area that identify any areas of defects (e.g., delaminations) detected in the substrate.
[0104] In some implementations, signal processing techniques may be based on machine learning to additionally process the data and extract relevant features from the audio record. For example, a

machine learning technique can be applied to the data and/or signals of acoustic responses in order to learn (e.g., develop algorithms or pattern recognition) how to identify material that may have one or more particular characteristics (e.g., due to being delaminated).

[0105] FIG. **11** is a spectrogram displaying results derived from acoustic response data collected during an acoustic excitation interrogation process in accordance with the process **1000**. The interrogation was performed on reinforced concrete slabs with intact and delaminated sections as the platform traversed along an edge of the slab. Acoustic responses were collected with a microphone and recorded. Post-processing to form the spectrogram was performed in MATLAB. In this spectrogram, no delamination is detected before approximately 6 seconds. Delamination is clearly detected after 7 seconds. In this spectrogram, it can be noted that the frequency bands at approximately 1 and 2 kHz correspond to the "hollow" sound of a natural delamination.

[0106] It should be appreciated that the process **1000** for operation of the acoustic excitation systems illustrated and described herein is not limited to the disclosed steps. For example, the process **1000** may be implemented differently with more or fewer steps, with additional steps that are not described herein, with one or more of the disclosed steps omitted, and so on in any combination. To illustrate, in an example of a different implementation the process **1000** may be differently implemented to operate the acoustic excitation systems of the instant disclosure by combining steps **1004** and **1006** to execute simultaneously. In another example of a different implementation of the process, the data processing of the data at step **1014** may be performed in real time as the interrogation is carried out, for example simultaneously with step **1008**. In such an implementation, map data corresponding to the interrogation may be provided to an operator of the acoustic excitation system, for example displayed on a screen.

[0107] It should further be appreciated that the acoustic exciters and acoustic excitation system illustrated and described herein are not limited to implementations in which lengths of chain are provided as the excitation elements. In some implementations, other types of elements may be provided for use in imparting acoustic excitation to a substrate. For example, in a different implementation, an acoustic exciter may include a contact element (e.g., of spherical and/or cylindrical shape) that is configured for triggering the acoustic excitation. In some implementations, a contact element may have another shape. For example, and without limitation, contact elements can be prismatic, triangular, or oval. For example, contact elements can include, but are not limited to, cylindrical, rod-shaped, spherical, elliptical, or rounded objects. The contact elements can be made of a suitably hard material, such as steel for example.

[0108] Implementations of the various techniques described herein may be implemented in digital electronic circuitry, or in computer hardware, firmware, software, or in combinations of them. Implementations may be implemented as a computer program product (e.g., a computer program tangibly embodied in an information carrier, a machine-readable storage device, a computer-readable medium, a tangible computer-readable medium) for processing by, or to control the operation of, data processing apparatus, e.g., a programmable processor, a computer, or multiple computers. In some implementations, a tangible computer-readable storage medium can be configured to store instructions that when executed cause a processor to perform a process. A computer program, such as the computer program(s) described above, can be written in any form of programming language, including compiled or interpreted languages, and can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program can be deployed to be processed on one computer or on multiple computers at one site or distributed across multiple sites and interconnected by a communication network.

[0109] In some implementations, process steps may be performed by one or more programmable processors executing a computer program to perform functions by operating on input data and generating output. In some implementations, process steps may be performed by, and an apparatus may be implemented as, special-purpose logic circuitry (e.g., an FPGA (field programmable gate array) or an ASIC (application-specific integrated circuit)).

[0110] Processors suitable for the processing of a computer program include, by way of example, both general and special-purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. Elements of a computer may include at least one processor for executing instructions and one or more memory devices for storing instructions and data. Generally, a computer also may include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data (e.g., magnetic, magneto-optical disks, or optical disks). Information carriers suitable for embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices (e.g., EPROM, EEPROM, and flash memory devices; magnetic disks (e.g., internal hard disks or removable disks); magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory may be supplemented by, or incorporated in special-purpose logic circuitry.

[0111] To provide for interaction with a user, implementations may be implemented on a computer having a display device (e.g., a cathode ray tube (CRT), a light emitting diode (LED), or liquid crystal display (LCD) device) for displaying information to the user and a keyboard and a pointing device, e.g., a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user, as well; for example, feedback provided to the user can be any form of sensory feedback (e.g., visual feedback, auditory feedback, or tactile feedback), and input from the user can be received in any form, including acoustic, speech, or tactile input.

[0112] Implementations may be implemented in a computing system that includes a back-end component (e.g., as a data server), or that includes a middleware component (e.g., an application server), or that includes a front-end component (e.g., a client computer having a graphical user interface or a Web browser through which a user can interact with an implementation), or any combination of such back-end, middleware, or front-end components. Components may be interconnected by any form or medium of digital data communication (e.g., a communication network). Examples of communication networks include a local area network (LAN) and a wide area network (WAN) (e.g., the Internet).

[0113] It will also be understood that when an element, such as a layer, a region, or a substrate, is referred to as being on, connected to, electrically connected to, coupled to, or electrically coupled to another element, it may be directly on, connected to, or coupled to the other element, or one or more intervening elements may be present. In contrast, when an element is referred to as being directly on, directly connected to, or directly coupled to another element or layer, there are no intervening elements or layers present. Although the terms directly on, directly connected to, or directly coupled to may not be used throughout the detailed description, elements that are shown as being directly on, directly connected, or directly coupled can be referred to as such. The claims of the application may be amended to recite exemplary relationships described in the specification or shown in the figures.

[0114] As used in this specification, a singular form may, unless definitively indicating a particular case in terms of the context, include a plural form. Spatially relative terms (e.g., over, above, upper, under, beneath, below, lower, and so forth) are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. In some implementations, the relative terms above and below can, respectively, include vertically above and vertically below. In some implementations, the term adjacent can include laterally adjacent to or horizontally adjacent to.

[0115] While certain features of the described implementations have been illustrated as described herein, many modifications, substitutions, changes, and equivalents will now occur to those skilled in the art. It is, therefore, to be understood that claims are intended to cover all such modifications and changes as fall within the scope of the implementations. It should be understood that they have been presented by way of example only, not limitation, and various changes in form and details may be made. Any portion of the apparatus and/or methods described herein may be combined in any combination, except mutually exclusive combinations. The implementations described herein can include various combinations and/or sub-combinations of the functions, components, and/or features of the different implementations described.

Claims

1. A system comprising: an acoustic exciter configured to be supported by a platform and having a plurality of excitation elements configured to rotate about an axis of rotation to cause acoustic excitation of a substrate via contact with the substrate, the acoustic exciter configured to be repositionable relative to the platform to alter an excitation path applied to the substrate by the excitation elements; and a sensor configured to sense an acoustic response of the acoustic excitation.
2. The system of claim 1, wherein the acoustic exciter includes: a head that is configured to support the plurality of excitation elements in a hanging arrangement; a shaft having a first end that is coupled to the head and a second end that is spaced from the first end, the shaft defining the axis of rotation; and a motor that is coupled to the second end of the shaft and configured to rotate the shaft around the axis of rotation.
3. The system of claim 2, wherein the acoustic exciter further includes: a coupler that is configured to mount the motor to the platform such that the motor is repositionable relative to the platform to vary an angle between the axis of rotation and a surface of the substrate.
4. The system of claim 3, wherein the coupler is configured to enable manual repositioning of the motor relative to the platform.
5. The system of claim 3, wherein the coupler is configured to enable automatic repositioning of the motor relative to the platform.
6. The system of claim 1, wherein altering the excitation path results from varying a quantity of the plurality of excitation elements that simultaneously make contact with the substrate.
7. The system of claim 1, further comprising: circuitry configured to determine at least one characteristic of the substrate based on the acoustic response.
8. The system of claim 1, wherein the sensor is a first sensor oriented to sense a first acoustic response caused at a first location by the plurality of excitation elements, and wherein the system further comprises: a second sensor oriented to sense a second acoustic response caused at a second location by the plurality of excitation elements.
9. The system of claim 8, further comprising: circuitry configured to determine at least one characteristic of the substrate based on the first acoustic response and the second acoustic response.
10. A system comprising: an acoustic exciter having a plurality of excitation elements, the acoustic exciter configured to maintain substantially continuous contact of the plurality of excitation elements with a substrate, the acoustic exciter including a motor that is configured to agitate the plurality of excitation elements to cause acoustic excitation of the substrate; and a sensor oriented to sense an acoustic response of the acoustic excitation.
11. The system of claim 10, wherein the motor is configured to agitate the plurality of excitation elements by rotating the excitation elements about an axis of rotation.
12. The system of claim 11, wherein the acoustic exciter is a first acoustic exciter and the plurality of excitation elements is a first plurality of excitation elements, and wherein the system further comprises: a second acoustic exciter having a second plurality of excitation elements, the second acoustic exciter configured to maintain substantially continuous contact of the second plurality of excitation elements with the substrate, the second acoustic exciter including a motor that is configured to agitate the second plurality of excitation elements to cause acoustic excitation of the

substrate; and a platform to which the first acoustic exciter and the second acoustic exciter are mounted, the platform configured to traverse the substrate along a direction of travel.

13. The system of claim 12, wherein the first acoustic exciter is mounted to the platform at a first location and causes acoustic excitation of a first area of the substrate, and wherein the second acoustic exciter is mounted to the platform at a second location and causes acoustic excitation of a second area of the substrate, the second location spaced from the first location such that the second area at least partially overlaps the first area.

14. The system of claim 12, wherein the sensor is a first sensor and the acoustic response is a first acoustic response associated with the first plurality of excitation elements, and wherein the system further comprises: a second sensor oriented to sense a second acoustic response associated with the second plurality of excitation elements.

15. The system of claim 14, further comprising: circuitry configured to determine at least one characteristic of the substrate based on the first acoustic response and the second acoustic response.

16. The system of claim 11, wherein the acoustic exciter includes: a head that is configured to support the plurality of excitation elements in a hanging arrangement; and a motor that is configured to rotate the excitation elements about the axis of rotation, wherein the axis of rotation is substantially orthogonal to a planar surface of the substrate.

17. An acoustic exciter comprising: a plurality of excitation elements that are configured to contact a substrate to cause acoustic excitation in the substrate; a head that is configured to support the plurality of excitation elements; a shaft having a first end that is coupled to the head and a second end that is spaced from the first end, the shaft defining an axis of rotation of the head; a motor that is coupled to the second end of the shaft and configured to rotate the shaft about the axis of rotation; and a coupler that is configured to mount the motor to a platform such that the motor is repositionable relative to the platform to vary an angle between the axis of rotation and a surface of the substrate.

18. The acoustic exciter of claim 17, wherein the head is configured to support the plurality of excitation elements in a hanging arrangement.

19. The acoustic exciter of claim 17, wherein the coupler is configured to enable at least one of longitudinal tilt and lateral tilt of the motor relative to the platform.

20. The acoustic exciter of claim 17, wherein the coupler comprises a ball head coupler.

21. The acoustic exciter of claim 17, wherein the coupler comprises a multi-axis positioner.

22. The acoustic exciter of claim 17, wherein the head comprises a plurality of attachment locations that are spaced apart from one another and configured to enable attachment of the plurality of excitation elements to the head.

23. The acoustic exciter of claim 22, wherein the plurality of excitation elements comprises a plurality of interconnected links.

24. The acoustic exciter of claim 23, wherein the head is configured such that when the plurality of interconnected links is suspended from the plurality of attachment locations, respective segments of the plurality of interconnected links exhibit sag between adjacent ones of the plurality of attachment locations.

25. The acoustic exciter of claim 22, wherein the plurality of excitation elements comprises a first segment of excitation elements and a second segment of excitation elements that is separate from the first segment, and wherein the head comprises a first attachment location configured to support the first segment of the plurality of excitation elements and a second attachment location configured to support the second segment of the plurality of excitation elements, the second attachment location spaced from the first attachment location.