

A SHEAROGRAPHY SYSTEM AND METHOD

FIELD OF INVENTION

[001] The present invention relates broadly, but not exclusively, to a shearography system and method.

BACKGROUND

[002] Non-destructive testing (NDT) of defects in materials is critical for various industries, such as aerospace, automobile, marine and offshore industries. The major defect types include fatigue cracks in metallic structures and delamination in multilayer composite materials, which may severely affect the reliability and safety of these materials. Therefore, early inspection of these defects by NDT is important for damage control, failure prediction and preventive maintenance.

[003] Examples of currently used NDT methods include ultrasonic, X-ray computed tomography and optical or thermal imaging methods. Ultrasonic method has high penetration power and good accuracy in determination of depth of defects; however, it is time-consuming and requires high level of expertise in data analysis. X-ray tomography is able to obtain 3D images of testing structure; but the radiation environment and high cost prevent its wide usage in field tests. Optical or thermal imaging method has the advantage of fast and full field imaging and direct visualization of defects; however, the detection is often limited to surface layer due to small penetration depth using conventional stress or thermal loading methods.

[004] Shearography is a full-field NDT imaging technique that can detect defects of a specimen by measuring the surface deformation abnormality under loading and unloading conditions. In a shearography testing, the interferometric digital image, known as the “speckle pattern”, of an unloaded specimen is obtained with a charge coupled device (CCD) camera. Subsequently, a stress field is introduced to the specimen and another interferometric digital image of the loaded specimen is obtained. By subtracting the two digital images of the specimen under loading and unloading conditions, a shearography image or shearogram is obtained. The shearogram is able to provide useful information for identifying defects, such as delamination, corrosions and cracks.

[005] The success of a shearography measurement is mainly dependent on the effective interaction between the defects and applied stress field, which can be reflected in the changes in surface deformation of the tested specimen. To apply stress to materials under shearography test, typically three loading methods have been developed, including partial vacuum and pressurization, vibrational excitation and thermal loading. These conventional loading methods have their limitations. The vacuum loading method requires that the testing materials are easy to deform and therefore does not work effectively for bulk rigid materials. The vibrational excitation loading method depends on the defect resonance to induce surface anomaly, which cannot be determined a priori. In addition, some defect resonance frequencies are too high to achieve experimentally. The thermal loading method has requirement on the thermal conductivity of materials under test. It is also time consuming as it takes a long time for the material to heat up and cool down.

[006] A need therefore exists to provide a shearography system and method that seek to address at least some of the above problems.

SUMMARY

[007] According to a first aspect, there is provided a shearography system comprising: an optical imaging device; and an acoustic transducer comprising an opening configured to be aligned with a region of interest on a sample, wherein the acoustic transducer is configured to apply acoustic loading on the sample based on one or more parameters; and wherein the optical imaging device is configured to image the region of interest with and without the acoustic loading through the opening.

[008] The system may further comprise a matching layer disposed between the acoustic transducer and the sample, the matching layer having an acoustic impedance matching the acoustic impedance of the acoustic transducer and the sample.

[009] The matching layer may comprise a pliant material configured to adapt to the shape of the acoustic transducer and the sample.

[0010] The acoustic transducer may comprise a plurality of transducer elements, and the transducer elements may be independently controllable.

[0011] The transducer elements may be configured to generate focused or directed acoustic waves in the region of interest.

[0012] The transducer elements may be configured to generate rotational acoustic waves in the region of interest.

[0013] The acoustic transducer may comprise a plurality of discrete transducer elements.

[0014] The acoustic transducer may comprise a concave surface.

[0015] The acoustic transducer may comprise an electromagnetic acoustic transducer (EMAT).

[0016] The acoustic transducer may comprise an air-coupled ultrasonic transducer.

[0017] The one or more parameters may comprise resonant frequency of the acoustic transducer and/or defect resonant frequencies.

[0018] The one or more parameters may comprise a depth into the sample, and the depth may be controlled by focusing an acoustic wave at the region of interest.

[0019] According to a second aspect, there is provided a shearography method comprising the steps of: providing an optical imaging device and an acoustic transducer, the acoustic transducer comprising an opening configured to be aligned with a region of interest on a sample; taking, by the optical imaging device, a reference first image of the region of interest while the acoustic transducer is not activated; applying, by activating the acoustic transducer, acoustic loading on the sample based on one or more parameters; taking, by the optical imaging device, a second image of the region of interest while the acoustic loading is applied; and generating an output based on an analysis of the reference first image and second image.

[0020] The method may further comprise the step of disposing a matching layer between the acoustic transducer and the sample, and the matching layer may have an acoustic impedance matching the acoustic impedance of the acoustic transducer and the sample.

[0021] The matching layer may comprise a pliant material, and disposing the matching layer may comprise adapting the matching layer to the shape of the transducer and the sample.

[0022] The acoustic transducer may comprise a plurality of transducer elements, and applying the acoustic loading on the sample may comprise independently controlling the plurality of the transducer elements.

[0023] Applying the acoustic loading on the sample may comprise generating focused or directed acoustic waves in the region of interest.

[0024] Applying the acoustic loading on the sample may comprise generating rotational acoustic waves in the region of interest.

[0025] The acoustic transducer may comprise a plurality of discrete transducer elements.

[0026] The acoustic transducer may comprise a concave surface.

[0027] The acoustic transducer may comprise an electromagnetic acoustic transducer (EMAT).

[0028] The acoustic transducer may comprise an air-coupled ultrasonic transducer.

[0029] Applying the acoustic loading on the sample based on one or more parameters may comprise selecting resonant frequency of the acoustic transducer and/or defect resonant frequencies.

[0030] Applying the acoustic loading on the sample based on one or more parameters may comprise selecting a depth into the sample, and the depth may be controlled by focusing an acoustic wave at the region of interest.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] Embodiments and implementations are provided by way of example only, and will be better understood and readily apparent to one of ordinary skill in the art from the following written description, read in conjunction with the drawings, in which:

[0032] Figure 1 is a schematic representation of a shearography system, according to an example embodiment.

[0033] Figure 2, comprising Figures 2(a) to 2(d), shows example results of applying the shearography system of Figure 1 to detect defects on a sample metal plate.

[0034] Figure 3, comprising Figures 3(a) to 3(c), is a schematic representation of multi-element acoustic transducers and an example simulation of acoustic wave propagation, according to another example embodiment.

[0035] Figure 4, comprising Figures 4(a) to 4(d), is a schematic representation of multi-element acoustic transducers for generating rotational acoustic wave, according to another example embodiment.

[0036] Figure 5, comprising Figures 5(a) and 5(b), is a schematic representation of acoustic transducers having multiple discrete transducer elements, according to another example embodiment.

[0037] Figure 6 is a schematic representation of multi-element acoustic transducers in non-closed shapes, according to another example embodiment.

[0038] Figure 7, comprising Figures 7(a) and 7(b), is a schematic representation of acoustic transducers with concave surfaces, according to another example embodiment.

[0039] Figure 8 is a schematic representation of a non-contact electromagnetic acoustic transducer (EMAT), according to another example embodiment.

[0040] Figure 9 shows example results of selective imaging of defects by applying a shearography system at local defect resonant frequencies.

[0041] Figure 10 shows a flow chart illustrating a shearography method according to an example embodiment.

DETAILED DESCRIPTION

[0042] Embodiments will be described, by way of example only, with reference to the drawings. Like reference numerals and characters in the drawings refer to like elements or equivalents.

[0043] Embodiments of the invention provide an integrated portable acoustic shearography system and the method of using the shearography system for non-destructive testing (NDT) of defects in materials and structures. The shearography system and method as disclosed herein can effectively combine the advantages of high penetration depth of ultrasonic waves and fast and full field direct visualization of shearography imaging system.

[0044] The system and method as disclosed advantageously have high penetration depth, no requirement on the sample's rigidity or thermal conductivity, and are independent of local defect resonances. The acoustic waves are generated by transducers integrated in the shearography system. The transducer can be designed to generate different types of acoustic waves for different testing purposes. Multi-element transducers are able to focus acoustic waves to different depth of the sample, such that enhanced signal is observed for subsurface defects. The driving frequencies of the transducer can be tuned to the resonance of transducers when all defects can be seen, or to the resonance of local defects such that different defect types can be differentiated.

[0045] As described in further details below, an acoustic transducer generate, in the example embodiments, acoustic waves in the testing structures that interact with defects to induce surface deformation anomalies where defects are present. The acoustic transducer may have an opening or channel in the center which allows light beam from an optical imaging device to pass through and defines field of view for defect detection. The transducer can be multi-element transducer whose concentric piezoelectric elements are patterned to generate focused or rotational acoustic waves to desired area. The transducer can comprise multiple pieces of small discrete transducer elements arranged in a ring shape or other closed shapes with an opening or channel in the center. The transducer can be in a non-closed shape to avoid possible obstacles on the surface of the sample or testing structure. The transducer can also be designed with concave surface such that the acoustic waves are naturally focused towards testing surface. The transducer can be electromagnetic acoustic

transducer operated in non-contact mode when the testing sample is metallic or magnetic. The transducer can also be air-coupled acoustic transducer.

[0046] The shearography system according to the example embodiments measures surface displacement anomaly by comparing interferometric images of the specimen under stress loading of ultrasonic waves with no stress loading conditions. The image under loading condition is taken when the acoustic transducers are activated to generate acoustic waves in a testing sample. Advantageously, large area and fast full field inspections can be done at resonant frequencies of the transducer. Different types of defects can also be differentiated by sweep driving frequencies around the defects' resonant frequencies. The non-destructive testing system in the example embodiments may integrate the shearography unit or optical imaging system with acoustic transducers in one portable enclosed unit.

[0047] Figure 1 is a schematic representation of a shearography system 100 according to an example embodiment. The shearography system 100 comprises at least an optical imaging device 102 and an acoustic transducer 104. The acoustic transducer 104 comprises an opening 106 configured to be aligned with a region of interest on a sample. Further, the acoustic transducer 104 is configured to apply acoustic loading on the sample based on one or more parameters. The optical imaging device 102 is configured to image the region of interest with and without the acoustic loading through the opening 106.

[0048] The shearography system 100 may be configured to be portable. The portable shearography system 100 includes an integration of two parts, the enclosed optical imaging device 102 and the acoustic transducer 104, in a portable unit. The optical imaging device 102 typically comprises a coherent laser as light source for optical imaging, an optics system of Michelson interferometer to form shearography and a charge coupled device (CCD) camera to collect the images. The acoustic transducer 104 is used to apply acoustic waves on the test sample with tunable wave modes and penetration depth. In one implementation, a matching layer 108 having an acoustic impedance matching the acoustic impedance of the acoustic transducer 104 and the test sample is used to effectively transmit acoustic waves into the test sample. The matching layer 108 may be made of pliant or soft materials, such as elastomer, to conform to curved surfaces and/or to adapt to the shape of the acoustic transducer 104 and the sample.

[0049] Figure 2, comprising Figures 2(a) to 2(d), shows example results of applying the shearography system 100 of Figure 1 to detect defects on a sample metal plate, according to an example embodiment. Figure 2(a) shows an optical image of a front side of an aluminum plate with four notches of 10 mm length around a hole of 8 mm in diameter. Figure 2(b) is a shearogram of the front side of the aluminum plate shown in Figure 2(a). Figure 2(c) shows an optical image of a back side of the aluminum plate of Figure 2(a). Figure 2(d) is a shearogram of the back side of the aluminum plate shown in Figure 2(c).

[0050] The acoustic transducer 104 used is a single element transducer made of piezoelectric ceramic of ring shape, with inner diameter of 38 mm. The metal plate is a 6 mm thick aluminum, with four notches of 10 mm length around a hole of 8 mm in diameter. The metal plate is tested from both front side where the notches are visible, and back side where the notches are not visible. A reference image is taken when the acoustic transducer 104 is off. During the shearography test, the acoustic transducer 104 is driven at its resonant frequency, which is pre-determined by electric impedance spectroscopy. The shearography image of deformed state of the sample is taken when the transducer 104 is activated at its resonant frequency and processed in a computer to generate the pattern of defects. The whole process only takes several seconds. As shown in Figure 2(b), all four notches are clearly observed from the front side. The length observed in the shearogram is approximately 10 mm, showing detection of the full notches. For the back side test, although the length observed in the shearogram is less than 10 mm as shown in Figure 2(d), all four notches are clearly visible.

[0051] Figure 3, comprising Figures 3(a) to 3(c), is a schematic representation 300 of multi-element acoustic transducers and an example simulation of acoustic wave propagation, according to another example embodiment.

[0052] Figures 3(a) and 3(c) are schematic representations of a 16-element acoustic transducer 302 and a 64-element acoustic transducer 306 respectively, having concentric piezoelectric elements that are patterned with a width matching a wavelength of acoustic waves in a sample. Figure 3(b) shows an example simulation of acoustic wave propagation 304.

[0053] The multi-element acoustic transducers as shown in Figure 3 can be used to generate acoustic waves for shearography test. Unlike conventional single element transducer, each transducer element of the multi-element transducers can be

independently controlled or individually activated at different times. By proper control of time delays between each element, the acoustic wave can be focused at desired directions and penetration depth. A large region/area of interest can be swept electronically without moving the transducer physically by controlling the direction of acoustic waves. In other words, the elements can generate focused acoustic waves to desired area and depth by tuning the time delay and frequencies of the driving voltage, enabling three-dimensional imaging of defects.

[0054] Figure 4, comprising Figures 4(a) to 4(d), is a schematic representation 400 of multi-element acoustic transducers for generating rotational acoustic wave, according to another example embodiment.

[0055] Figure 4(a) is a schematic representation of an 8-segment transducer for generating rotational acoustic wave. Figure 4(b) shows an example simulated surface displacement when the transducer of Figure 4(a) is activated with proper time delay. Figure 4(c) is a schematic representation of a 16-segment transducer which the segments are arranged along circumferential direction for generating rotational acoustic wave. Figure 4(d) is a schematic representation of a 16-segment transducer in which the segments are arranged in two layers of 8 segments along circumferential direction for generating rotational acoustic wave.

[0056] The multi-element transducers as shown in Figure 4 have transducer elements configured to generate rotational acoustic waves for shearography test. Each transducer element of the multi-element transducers can be independently controlled. In real industry samples, the directions of defects are unknown. To maximize the interaction between acoustic waves and defects, a rotational acoustic wave can be used, as its propagation direction is continuously changed to cover full 360 degrees. By proper control of time delay in radial and circumferential directions, rotational acoustic waves are generated to effectively interact with defects in all in-plane directions.

[0057] Figure 5, comprising Figures 5(a) and 5(b), is a schematic representation 500 of acoustic transducers having multiple discrete transducer elements 502, 504 according to another example embodiment. Figure 5(a) shows discrete transducers elements 502 arranged in a ring shape and Figure 5(b) shows discrete transducers elements 504 arranged in a rectangular shape.

[0058] In some applications, acoustic transducers having multiple discrete transducer elements 502, 504 as shown in Figure 5 can be used generate acoustic waves for shearography test. For example, in the case where the region of interest is too large to fabricate a transducer in a whole piece, small discrete transducers elements 502, 504 can be arranged in desired shapes to generate desired acoustic waves. The transducers 502, 504 can be arranged in various shapes or formations with an opening or channel in the center for shearography test. The individual discrete transducer elements 502, 504 themselves can be in various shapes, such as circle and square. This may advantageously save cost for transducer fabrication and also provide additional flexibility in transducer design.

[0059] Figure 6 is a schematic representation 600 of multi-element acoustic transducers in non-closed shapes, according to another example embodiment. The multi-element transducer in non-closed shapes as shown in Figure 6 can be useful in certain applications. For example, in the case where the closed shape of transducer is not practical due to obstacles on surface of the testing structure, or part of the region of interest is not accessible in certain direction, non-closed transducers, for example, an arc or semicircle, can be used. Even though the transducer is not in a closed shape, the acoustic waves can still be effectively focused to certain directions, for example towards the center of arc or semi-circle.

[0060] Figure 7, comprising Figures 7(a) and 7(b), is a schematic representation 700 of acoustic transducers with concave surfaces 702, according to another example embodiment. Figure 7(a) is a cross-sectional view of a transducer with concave surface 702. Figure 7(b) is a schematic representation of a transducer with concave surface 702 that is configured with an opening or channel in the center and fitted with a matching layer 704.

[0061] The transducer comprising concave surface 702 as shown in Figure 7 can be single-element or multi-element. The transducer with concave surface 702 naturally focuses the acoustic waves to the sample under test. In one implementation, to effectively transmit the acoustic waves to the testing sample, the matching layer 704 having an acoustic impedance matching the acoustic impedance of the acoustic transducer 702 and the sample is used. The matching layer 704 has a shape that matches the curved surface of transducer 702 on one side, and has a flexible adaptable surface (such as that of an elastomer) on the other side, in order to conform

to the testing surface. The focused direction can be tunable when multi-element transducers comprising concave surface 702 are used.

[0062] Embodiments of the invention may also use acoustic transducers that comprise air-coupled ultrasonic transducers. The air-coupled ultrasonic transducers may have arrangements similar to those of the above described embodiments.

[0063] Figure 8 is a schematic representation 800 of a non-contact electromagnetic acoustic transducer (EMAT) 802, according to another example embodiment. EMAT 802 can be practical in certain applications. For example, in the case where direct contact of the transducer with the testing surface is not applicable and the testing sample is metallic or magnetic, EMAT 802 can be used to generate acoustic waves without contact by electromagnetic mechanism. EMAT 802 can be designed in ring shape and have an opening or channel in the center for shearography imaging.

[0064] Examples of the parameters of the shearography system according to the example embodiment include, but are not limited to, resonant frequency of the acoustic transducer, defect resonant frequencies and penetration depth into the sample. The penetration depth may be controlled by focusing an acoustic wave at the region of interest.

[0065] Figure 9 shows a schematic representation 900 illustrating example results of selective imaging of defects 902 by applying the present shearography system at local defect resonant frequencies. In addition to driving the transducer at its resonant frequency to maximize output power, it is also useful to sweep the driving frequencies around defect resonant frequencies to differentiate different type of defects. Due to the existence of defects, local mechanical properties such as stiffness are different from defect-free parts, leading to characteristic defect specific resonant frequencies. For example, square defects 902 with different thicknesses can be selectively observed by using driving frequencies at their respective resonant frequencies. This defect resonant mode of shearography operation advantageously consumes lower power.

[0066] Embodiments of the invention also provide a shearography method. Figure 10 shows a flow chart 1000 illustrating a shearography method according to an example embodiment. At step 1002, an optical imaging device and an acoustic transducer are provided. The acoustic transducer comprises an opening that is configured to be aligned with a region of interest on a sample. At step 1004, a reference first image of

the region of interest is taken by the optical imaging device while the acoustic transducer is not activated. At step 1006, acoustic loading is applied on the sample by activating the acoustic transducer based on one or more parameters. At step 108, a second image of the region of interest is taken by the optical imaging device while the acoustic loading is applied. At step 1010 an output is generated based on an analysis of the reference first image and second image.

[0067] It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A shearography system comprising:
an optical imaging device; and
an acoustic transducer comprising an opening configured to be aligned with a region of interest on a sample,
wherein the acoustic transducer is configured to apply acoustic loading on the sample based on one or more parameters; and
wherein the optical imaging device is configured to image the region of interest with and without the acoustic loading through the opening.
2. The shearography system as claimed in claim 1, further comprising a matching layer disposed between the acoustic transducer and the sample, the matching layer having an acoustic impedance matching the acoustic impedance of the acoustic transducer and the sample.
3. The shearography system as claimed in claim 2, wherein the matching layer comprises a pliant material configured to adapt to the shape of the acoustic transducer and the sample.
4. The shearography system as claimed in any one of claims 1 to 3, wherein the acoustic transducer comprises a plurality of transducer elements, and wherein the transducer elements are independently controllable.
5. The shearography system as claimed in claim 4, wherein the transducer elements are configured to generate focused or directed acoustic waves in the region of interest.
6. The shearography system as claimed in claim 4, wherein the transducer elements are configured to generate rotational acoustic waves in the region of interest.
7. The shearography system as claimed in any one of claims 1 to 3, wherein the acoustic transducer comprises a plurality of discrete transducer elements.
8. The shearography system as claimed in any one of the preceding claims, wherein the acoustic transducer comprises a concave surface.
9. The shearography system as claimed in claim 1, wherein the acoustic transducer comprises an electromagnetic acoustic transducer (EMAT).

10. The shearography system as claimed in any one of claims 1 to 8, wherein the acoustic transducer comprises an air-coupled ultrasonic transducer.
11. The shearography system as claimed in any one of the preceding claims, wherein the one or more parameters comprise resonant frequency of the acoustic transducer and/or defect resonant frequencies.
12. The shearography system as claimed in any one of the preceding claims, wherein the one or more parameters comprise a depth into the sample, wherein the depth is controlled by focusing an acoustic wave at the region of interest.
13. A shearography method comprising the steps of:
 - providing an optical imaging device and an acoustic transducer, the acoustic transducer comprising an opening configured to be aligned with a region of interest on a sample;
 - taking, by the optical imaging device, a reference first image of the region of interest while the acoustic transducer is not activated;
 - applying, by activating the acoustic transducer, acoustic loading on the sample based on one or more parameters;
 - taking, by the optical imaging device, a second image of the region of interest while the acoustic loading is applied; and
 - generating an output based on an analysis of the reference first image and second image.
14. The shearography method as claimed in claim 13, further comprising the step of disposing a matching layer between the acoustic transducer and the sample, wherein the matching layer has an acoustic impedance matching the acoustic impedance of the acoustic transducer and the sample.
15. The shearography method as claimed in claim 14, wherein the matching layer comprises a pliant material, and wherein disposing the matching layer comprises adapting the matching layer to the shape of the transducer and the sample.
16. The shearography method as claimed in any one of claims 13 to 15, wherein the acoustic transducer comprises a plurality of transducer elements, and wherein applying the acoustic loading on the sample comprises independently controlling the plurality of the transducer elements.

17. The shearography method as claimed in claim 16, wherein applying the acoustic loading on the sample comprises generating focused or directed acoustic waves in the region of interest.

18. The shearography method as claimed in claim 16, wherein applying the acoustic loading on the sample comprises generating rotational acoustic waves in the region of interest.

19. The shearography method as claimed in any one of claims 13 to 15, wherein the acoustic transducer comprises a plurality of discrete transducer elements.

20. The shearography method as claimed in any one of claims 13 to 19, wherein the acoustic transducer comprises a concave surface.

21. The shearography method as claimed in claim 13, wherein the acoustic transducer comprises an electromagnetic acoustic transducer (EMAT).

22. The shearography method as claimed in any one of claims 13 to 20, wherein the acoustic transducer comprises an air-coupled ultrasonic transducer.

23. The shearography method as claimed in any one of claims 13 to 22, wherein applying the acoustic loading on the sample based on one or more parameters comprises selecting resonant frequency of the acoustic transducer and/or defect resonant frequencies.

24. The shearography method as claimed in any one of claims 13 to 23, wherein applying the acoustic loading on the sample based on one or more parameters comprises selecting a depth into the sample, wherein the depth is controlled by focusing an acoustic wave at the region of interest.