Chapter 5
Applications of Temporal Phase Shift Shearography

The main applications of temporal phase shift shearography are in NDT and strain measurement.

5.1. Temporal Phase Shift Shearography for NDT

The most important application of temporal phase shift shearography, called digital shearography for simplicity, is for NDT, which enables flaws in objects/materials to be found without damaging them. Compared to conventional NDT methods, such as ultrasonic, radiographic, magnetic article, dye penetrant, eddy current, and acoustic emission methods, digital shearography has the advantages of full-field measurement, high sensitivity, easy visualization, quick measurement speed, and real-time display of test results. Due to these distinct advantages, digital shearography has been widely accepted by the automotive and aerospace industries as a recommended NDT method for rubber and composite materials.[1–2] The details of digital shearography for NDT have been described and discussed in Refs. 3 and 4. In this section, potentials and limitations of temporal phase shift shearography for NDT are reviewed, practical applications using different loading methods are demonstrated, and a few recent developments, such as NDT for testing relatively large objects and for measuring mirror-like surfaces, are presented and discussed.

5.1.1 Potentials and limitations of temporal phase shift shearography

5.1.1.1 Temporal phase shift shearography versus electronic shearography

Digital shearography includes simple digital subtraction technology (or so-called electronic shearography), temporal phase shift shearography, and spatial phase shift shearography, which will be described in the next chapters. As discussed in Chapter 4, temporal phase shift shearography uses the phase shift technique, in which phase distribution at each pixel is quantitatively determined to generate a phase map of the shearogram; whereas, electronic shearography, or

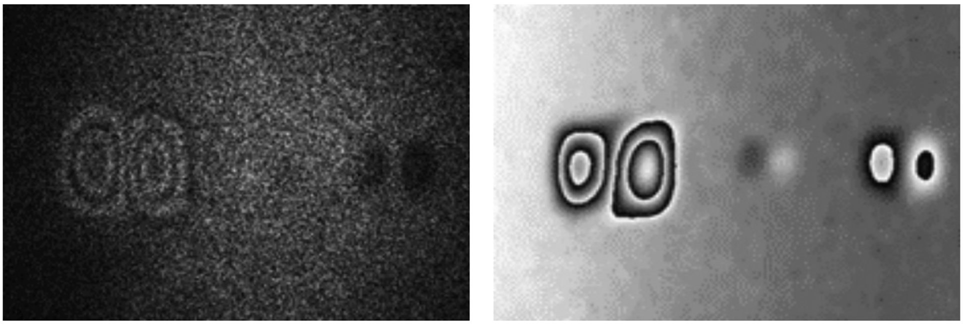

Figure 5.1 Intensity fringe pattern versus phase map of shearography for NDT of a composite plate with the same vacuum loading amount. (a) The smallest delamination in the middle is not visible in the intensity mode. (b) All three delaminations are clearly identified in the phase map.

TV-shearography, creates an intensity fringe pattern through a direct digital subtraction of two intensity images recorded by the shearographic setup before and after loading. In the intensity fringe pattern, phases, of which the smallest measurable phase value is 2π, can be measured only at the locations of the fringe orders. However, for the phase map mode, phases can be measured quantitatively at locations of each pixel, resulting in much higher spatial resolution. Also, theoretically, the phase determination can reach down to 2π/256 if the digitization resolution of the system is 8 bit. Although it is practically difficult to reach this value due to speckle noise, it is easy to reach a measurement sensitivity from 2π/20 to 2π/10, depending on the utilization of different PZT drivers, algorithms, smoothing methods, etc.[5] Obviously, phase shift digital shearography has much higher spatial resolution and sensitivity for measuring phase distribution than electronic versions of shearography. This gives greater capability in finding deeper and smaller defects in materials than can be found using electronic shearography.[6] Figure 5.1 shows shearographic measurement results for a composite plate with three delaminations. The smallest delamination was not visible in the intensity fringe pattern but can be clearly identified in the phase map, even though both tests utilized the same vacuum loading amount.

5.1.1.2. Fringe enhancement and multiplication technique

In the phase map of a shearogram generated by the temporal phase shift technique, the phase value at each pixel is quantitatively determined, which enables the phase map to be further processed, e.g., fringe enhancement and multiplication. For an 8-bit hardware resolution, there are 256 gray levels within one fringe (from black to white). The multiplication of the fringe number can be achieved using the following modulo operation:

$$G'(x,y) = [G(x,y) \times M] \bmod 256, \tag{5.1}$$

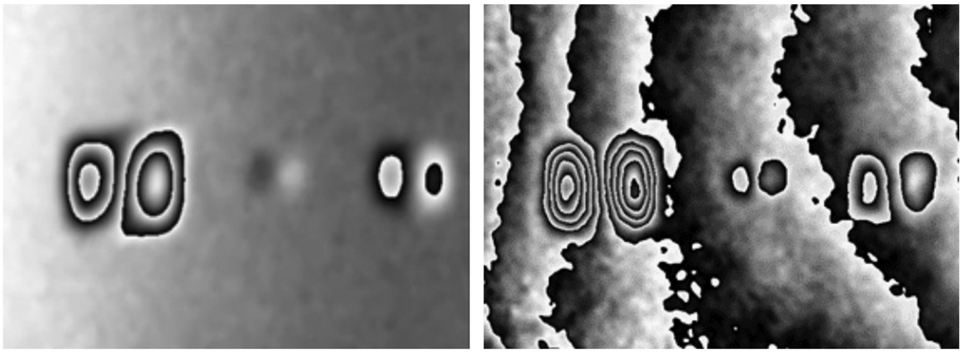

Figure 5.2 Method for fringe enhancement and multiplication: (a) smoothed phase map of the shearogram revealing three delaminations in a composite plate by vacuum loading; (b) multiplied fringe pattern with M set to 3.

where $G'(x, y)$ is the gray level in the new phase map after multiplication, $G(x, y)$ is the gray level of the original phase map, M is the multiplication number, and mod means modulo operation.

$[G(x, y) \times M]$ modulo 256, abbreviated as $[G(x, y) \times M]$ mod 256, can be thought of as the remainder resulting from the division of $[G(x, y) \times M]$ by 256. For instance, if $G(x, y) = 250$, and $M = 3$, $[G(x, y) \times M] = 750$, and the expression "750 mod 256" would have a result of 238 because 750 divided by 256 leaves a remainder of 238. After this operation, the fringe number will be increased by a factor of M.

If the hardware resolution is 10 bit, then 1024 gray levels exist within one fringe, and Eq. (5.1) becomes

$$G'(x, y) = [G(x, y) \times M] \bmod 1024. \tag{5.2}$$

For better understanding of the concept described above, an example is provided. Figure 5.2(a) presents a smoothed shearogram phase map revealing three delaminations in a composite plate by vacuum loading. Figure 5.2(b) shows the multiplied fringe pattern of Fig. 5.2(a) with M set to 3. Obviously, the fringe multiplication technique can be used to enhance flaw visibility for NDT applications, especially to enhance the visibility of small flaws.

5.1.1.3 Determining bending strain

As a component of a digital technique, the phase map of a shearogram can be further quantitatively evaluated to obtain the second derivative of out-of-plane deformation, which is related to a bending strain, by means of a numerical differentiation of the phase map. Shearography measures the first derivatives of out-of-plane deformation, $\partial w/\partial x$ or $\partial w/\partial y$, directly. They are

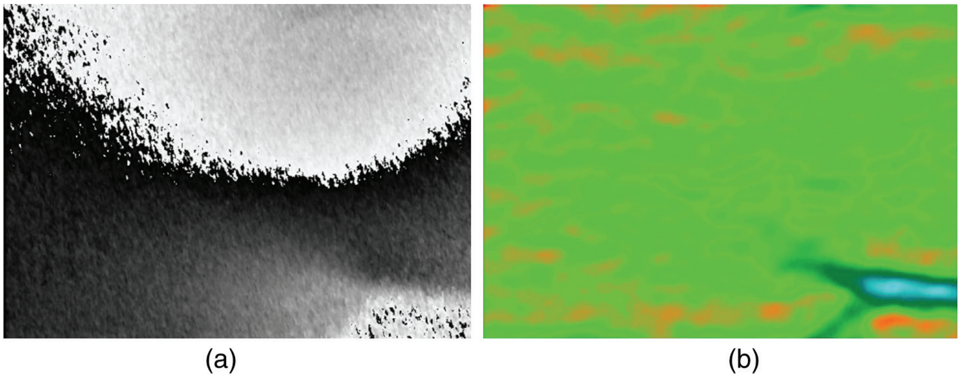

Figure 5.3 Shearographic NDT using a thermal loading for a carbon-reinforced plate with a micro-crack. (a) The micro-crack appears blurred in the phase map of the shearogram. (b) The micro-crack appears clearly in the second derivatives of deformation, i.e., the bending strain.

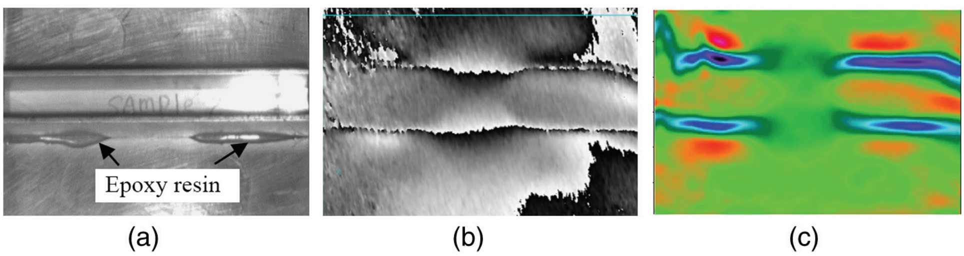

Figure 5.4 Bending strain makes an ambiguous result clear: (a) a photo of an aluminum plate from backside, (b) the phase map of the shearogram revealing a first derivative of out-of-plane deformation, and (c) the image depicting the second derivative of out-of-plane deformation, i.e., a bending strain.

two terms of a strain matrix, but neither $\partial w/\partial x$ nor $\partial w/\partial y$ is a strain value. A bending strain for structures of thin plates and thin panels is related to the second derivation of out-of-plane deformation rather than the first derivation. In many cases, strain concentration is more directly identified in the distribution of bending strain than in the shearogram if an object to be tested is a thin plate or thin panel. Therefore, a display of second derivative of out-of-plane deformation makes results (in some cases that are ambiguous in the shearogram) easier to interpret.

Figure 5.3 shows a shearographic test performed on a reinforced carbon plate with a micro-crack. The micro-crack appears blurred in the phase map of a shearogram depicting $\partial w/\partial y$ [Fig. 5.3(a)]. However, the position and size of the micro-crack appear clearly in the image of second derivatives of deformation ($\partial^2 w/\partial y^2$), i.e., the bending strain [Fig. 5.3(b)].

Figure 5.4 demonstrates shearographic NDT for a thin aluminum plate. A reinforced beam was glued to the plate with epoxy resin on its backside.

The epoxy resin was applied to the top and bottom positions of the beam on both the left and right sides, but not in the middle. Figure 5.4(a) is a photo of the backside of the plate. The positions of epoxy resin are displayed clearly on both sides of the bottom of the beam, but not at the top of the beam because of a shadow. The front of the plate was measured using a thermal load. The glued positions are ambiguous, as seen from the shearogram result [Fig. 5.4(b)], whereas they were very clearly identified from the image of a second derivation of out-of-plane deformation, i.e., a bending strain image [Fig. 5.4(c)].

5.1.1.4 Step-by-step measurement

Step-by-step measurement is a special advantage of phase shift shearography that enables shearographic inspection under a relatively large loading magnitude. The loading magnitude might need to be increased to detect smaller and deeper defects in an object. Increasing the loading magnitude can cause intolerable rigid-body movements. Although shearography is relatively insensitive to rigid-body movement, a rigid-body movement that is too large would cause speckle decorrelation, resulting in degradation of the shearogram.[7–8] This limitation can be overcome by taking a step-by-step test procedure, then adding all shearograms together. It should be noted that this operation does not work with electronic shearography, but works with phase shift shearography because the phase distribution of each shearogram is quantified and the phase maps taken at each steps can, thus, be quantitatively added together.

5.1.1.5 Other potentials of phase shift shearography and its limitations

Besides the advantages described above, temporal phase shift shearography enjoys most of the advantages of conventional photographic and electronic shearography,[9–11] such as

- full-field, noncontacting, and noncontaminating NDT method,
- simple in optical setup due to its self-referencing optical system,
- usable with multiple laser diodes for illumination, which greatly reduces cost,
- insensitive to rigid-body motions and well suited for real-world applications, and
- direct measurement of strain information, making it easy to find defects that generate a strain concentration under a suitable loading.

As an NDT tool, digital shearography is becoming more and more accepted by the automotive and aerospace industries. It has demonstrated great potential in revealing delaminations for different materials, especially for composite materials, honeycomb structures, and thin plates.

Of course, like other techniques, digital shearography also has its limitations. Digital shearography is an experimental technique for surface