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Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems[1]

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1. Scope

1.1 The purpose of this document is to assist potential users in understanding the issues related to the accuracy of non-contacting strain measurement systems and to provide a common framework for quantitative comparison of optical systems. The output from a non-contacting optical strain and deformation measurement system is generally divided into optical data and image analysis data. Optical data contains information related to specimen strains and the image analysis process converts the encoded optical information into strain data. The enclosed document describes potential sources of error in the strain data and describes general methods for quantifying the error and estimating the accuracy of the measurements when applying non-contacting methods to the study of events for which the optical integration time is much smaller than the inverse of the maximum temporal frequency in the encoded data (that is, events that can be regarded as static during the integration time). A brief application of the approach, along with specific examples defining the various terms, is given in the Appendix.

2. Referenced Documents

2.1 *ASTM Standards:*

E 8 Test Methods for Tension Testing of Metallic Materials[2]

E 83 Practice for Verification and Classification of Extensometers[2]

E 251 Test Methods for Performance Characteristic of Bonded Resistance Strain Gages[2]

E 399 Test Method for Plane Strain Fracture Toughness of Metals[2]

E 1823 Terminology Relating to Fatigue and Fracture Testing[2]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *accuracy*—quantitative relationship of the measurements to the value obtained by standard measurement techniques

3.1.2 *basic data*—data obtained directly by the measurement system. For optical, non-contacting methods, a two-dimensional array of image intensity data is generally the basic data.

3.1.3 *coherent illumination*—light source where the difference in phase is solely a function of optical path differences; interference is a direct consequence.

3.1.4 *decoded data*—measurement information related to the displacement or displacement gradient field.

3.1.5 *decoded data bandwidth*—spatial frequency range of the information after decoding of the optical data.

3.1.6 *derived data*—data obtained through processing of the basic data. Typically, this is displacement field data.

3.1.7 *dynamic range*—the range of physical parameter values for which measurements can be acquired with the measurement system.

3.1.8 *illumination wavelength*—wavelength of illumination, ζ.

3.1.9 *incoherent illumination*—light source with random variations in optical path differences; constructive or destructive interference of waves is not possible.

3.1.10 *maximum temporal frequency of encoded data*—reciprocal of the shortest event time contained in the encoded data (for example, time variations in displacement field).

3.1.11 *measurement noise*—variations in the measurements that are not related to actual changes in the physical property being measured. May be quantified by statistical properties such as standard deviation.

3.1.12 *measurement resolution*—smallest change in the physical property that can be reliably measured.

3.1.13 *numerical aperture, (N.A.)*—non-dimensional measure of diffraction-limitation for imaging system; N.A. = D/f for a simple lens system, where D is lens diameter and f is lens focal length.

3.1.14 *optical data*—recorded images of specimen, containing encoded information related to the displacement or displacement gradient field, or both.

[1] This guide is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.03 on Advance Apparatus and Techniques.

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[2] *Annual Book of ASTM Standards*, Vol 03.01.

3.1.15 *optical data bandwidth*—spatial frequency range of the optical pattern (for example, fringes, speckle pattern, etc.) that can be recorded in the images without aliasing or loss of information.

3.1.16 *optical integration time*—time over which digital image data is averaged to obtain a discretely sampled representation of the object.

3.1.17 *optical resolution, (OR)*—distance, $d = \zeta / (2 \text{ N.A.})$, between a pair of lines that can be quantatively determined.

3.1.18 *quantization level*—number of bits used in the digital recording of optical data by each sensor for image analysis. The quantization level is one of the parameters determining the fidelity of the recorded optical images. It is determined by the camera selected for imaging and typically is 8 bits for most cameras.

3.1.19 *recording resolution (pixels/length)*, κ—number of optical sensor elements (pixels) used to record an image of a region of length L on object.

3.1.20 *spatial resolution for encoded data*—one-half of the period of the highest frequency component contained in the frequency band of the encoded data.

3.1.21 *spatial resolution for optical data*—one-half of the period of the highest frequency component contained in the frequency band of the optical data. Note that decoded data may have a lower spatial resolution due to the decoding process.

3.1.22 *systematic errors*—biased variations in the measurements due to the effects of test environment, hardware and/or software. Test environment effects include changes in temperature, humidity, lighting, out-of-plane displacements (for 2-D systems) etc. Hardware effects include lens aberrations, thermal drift in recording media, variations in sensing elements, interlacing of lines, phase lag due to refresh rates, depth of field for recording system, etc. Software effects include interpolation errors, search algorithm processes, image boundary effects, etc.

4. Description of General Optical Non-Contacting Strain Measurement Systems

4.1 Figs. 1 and 2 show schematics of typical moiré and digital image correlation setups used to make displacement field measurements. In its most basic form, an optical non-contacting strain measurement system such as shown in Figs. 1 and 2, consists of five components. The five components are (*a*) an illumination source, (*b*) a test specimen, (*c*) a method to apply forces to the specimen, (*d*) a recording media to obtain images of the object at each load level of interest and (*e*) an image analysis procedure to convert the encoded deformation information into strain data. Since the encoded information in the optical images may be related either to displacement field components or to the displacement gradient field components, image analysis procedures will be somewhat different for each case. However, regardless of which form is encoded in the images, the images are the Basic Data and the displacement fields and the strain fields will be part of the Derived Data. This guide is primarily concerned with general features of (*a*) the illumination source, (*d*) image recording components, and (*e*) image analysis procedures. ASTM standards for specimen design and loading, such as Test Methods E 8 for tensile testing of metals or Test Method E 399 for plane strain fracture toughness provide the basis for (*b*, *c*).

5. Error Sources

5.1 At each stage of the flow of data in the measurement system, errors can be introduced. These are considered in the sequence in which they occur in this guide.

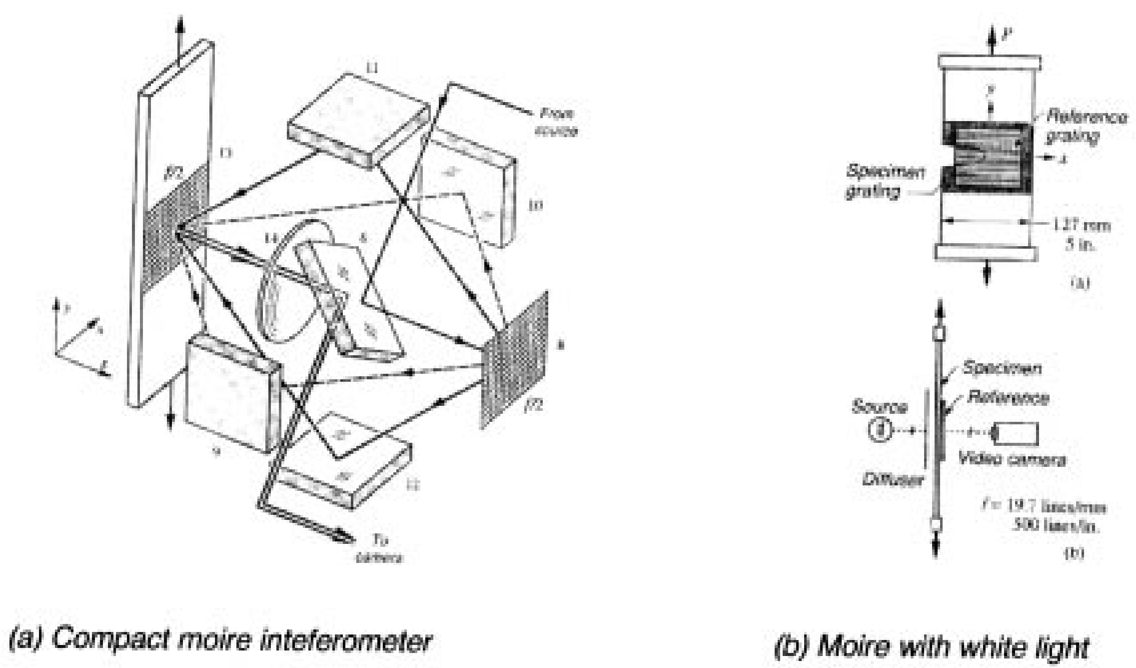

FIG. 1 Typical Optical Moiré Systems for In-Plane Displacement Measurement

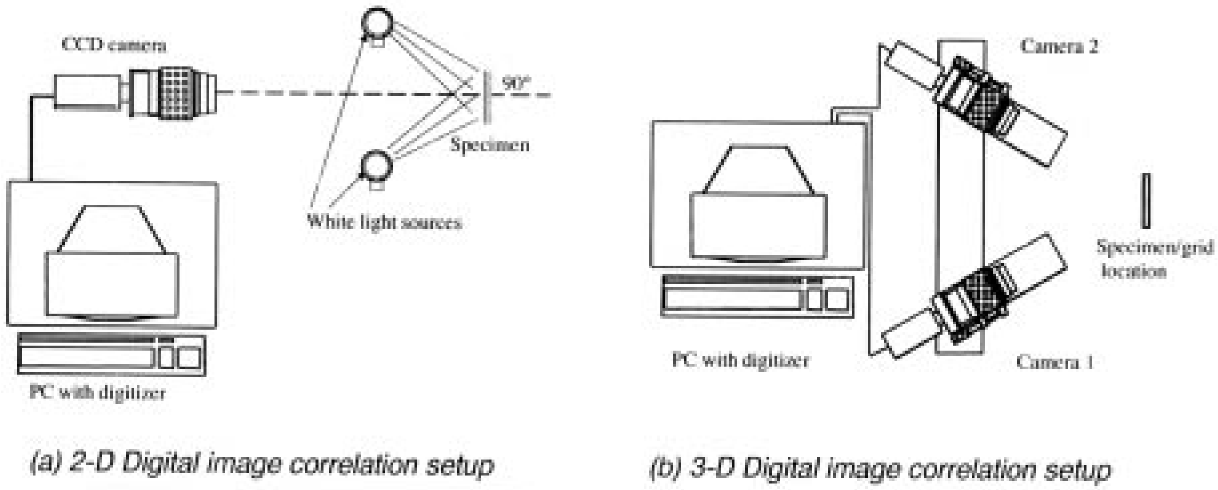

FIG. 2 Typical Digital Image Correlation Setups For (*a*) In-Plane Displacement Measurement and (*b*) Three-Dimensional Displacement Measurement

5.2 *Errors Introduced in Recording Process*—Since the media used to record Basic Data can introduce additional errors in the Derived Data, each set of experimental data must include a detailed description of the recording media used. If a digital camera system is used to record images, data to be included should be the camera manufacturer, camera output form (for example, analog or digital), camera spatial resolution, data acquisition board type, pixel quantization level (for example, 8 bits), ratio of pixel dimensions, lens type and manufacturer. When photographic film is used to record images, the film characteristics and method of processing, as well as lens type and manufacturer used in imaging should be documented.

5.3 *Errors Due to Extraneous Vibrations*—Depending upon the measurement resolution, system vibrations can increase errors in the encoded information which may result in additional extraction errors. Provided that the period of vibration is sufficiently small relative to the integration time, and the amplitude of the disturbance is small relative to the quantity being measured, sensor averaging may reduce the effect of vibrations on the displacement fields and the strain fields.

5.4 *Errors Due to Lighting Variations*—Since the Basic Data is image data, lighting variations during the experiment may affect (*1*) the actual encoded information (for example, phase shift in coherent methods) and (*2*) extraction of the encoded information. For incoherent methods, light variations of several quantization levels may degrade the Derived Data extracted from the images. Similar effects are possible for coherent methods if there are, for instance, slight changes in the wavelength of the illumination. In both cases, use of image processing methods that are insensitive to lighting variations (for example, normalized cross correlation) will increase the accuracy of the extracted data.

5.5 *Errors Due to Rigid Body Motion*—Depending upon the measurement resolution, rigid body translation and/or rotation may severely impact the ability to extract encoded information from the image data. For example, if the translation is large compared to the measurement resolution and the optical resolution of the recording media is low, then the high frequency encoded information may be lost.

5.6 *Errors in Extraction Process*—The encoded information extracted from the recorded images is degraded by errors introduced by the image processing method used. Errors introduced by the extraction process can be a combination of random errors as well as systematic errors (for example, peak-estimator bias or drift in Fourier correlation methods). Improved methods for image processing may significantly reduce extraction errors and special care should be taken to reduce systematic errors.

5.6.1 For example, one can define an engineering measure of normal strain along the "*n*" direction as:

$$\epsilon_{nn} = \frac{(L_n^{final} - L_n^{initial})}{L_n^{initial}}$$

Here, ϵ_{nn} is defined by $L_n^{final} = [(L_n + \Delta u_n)^2 + (\Delta u_{t1})^2 + (\Delta u_{t2})]^{1/2}$ and $(\Delta u_n, \Delta u_{t1}, \Delta u_{t2})$ are finite changes in displacement along the perpendicular directions n, t_1 and t_2 for points at either end of line L_n. Thus, errors in strain ϵ_{nn} can be due to (*1*) errors in the initial length of the line element and (*2*) errors in the displacement components $(\Delta u_n, \Delta u_{t1}, \Delta u_{t2})$. In both cases, extraction of Derived Data from the Basic Data is the source of error.

5.7 *Errors in Processing Extracted Data*—Errors are introduced when the form of extracted Derived Data in 5.6 is processed to obtain strain data. This process can involve a wide range of mathematical operations including (*1*) numerical differentiation of derived displacement data and (*2*) smoothing of displacement or displacement gradient data. Errors introduced by the choice of post-processing method can include, but are not limited to, (*1*) reduction of spatial resolution, (*2*) systematic under-prediction of strain in areas of high strain gradients, (*3*) phase errors in the signal due to non-symmetric operators etc.

6. System Evaluation Process

6.1 Each non-contacting optical strain measurement system must be evaluated to determine reliable estimates for the accuracy of the resulting Derived Data. Given the wide range of methods that have been developed, this guide will not address specific details involving the application of any technique. Rather, the guidelines are provided as a general framework for evaluation of non-contacting optical strain measurement systems.

6.2 In the following sections, a direct comparison between established measurement methods and non-contacting methods is recommended. However, it must be noted that, even though this approach does provide a direct, quantitative measure of agreement between two, independent measurement data sets. Practice E 83 and Test Methods E 251 provide only average values for strain over a specific area on the specimen. Thus, good agreement with the average value obtained from the Derived Data in the same area does not verify (*1*) the accuracy of local variations observed in the Derived Data or (*2*) the accuracy of the Derived Data in regions outside the area where comparisons were made.

6.2.1 For example, if a finite difference in displacement components is used to determine strain components such as ϵ_{nn}, then errors in relative displacement components can be directly related to strain errors using equations such as:

$$E\epsilon_{nn} \cong \frac{\Delta L_n^{final}}{L_n^{initial}}$$

Where $E\epsilon_{nn}$ is an estimate for the error in the normal strain ϵ_{nn}. Here, ΔL_n^{final} is the error in final length due to errors in the measured displacement components. Through calibration, the contribution of inaccuracies in the relative displacement components (Δu_n, Δu_{t1}, Δu_{t2}) to strain error can be determined. However, the accuracy of the Derived Data outside of this region, which may be a region of importance, cannot be verified without additional comparisons.

6.3 *Comparison to Standard Measurement Methods for Similar Test Conditions*—Non-contacting measurements can be made under diverse conditions (for example, high temperature, in-situ structures, laboratory test frames, vacuum). Due to the diversity of conditions, calibration tests are recommended on similar components under similar conditions to assess accuracy. In this approach, the effects of those phenomena present in the test condition but not accounted for in laboratory tests or computer simulations are directly included in the error assessment.

6.3.1 For these tests, direct comparison of the non-contacting measurements to independent measurements by established methods using documented ASTM procedures (for example, extensometers (Practice E 83), strain gages (Test Methods E 251)) whenever possible is the most reliable way to obtain quantitative estimates for the accuracy of average values obtained from the Derived Data. If this approach is used, all data acquisition and analysis procedures must remain the same as used in the actual tests, with clear documentation provided to demonstrate that the same procedure has been used for both tests.

6.4 *Comparison to Standard Measurement Methods for Simulated Test Conditions in Laboratory Environments*—For those cases where laboratory tests can be used to approximate actual test conditions, calibration tests should be performed on laboratory specimens for accuracy assessment. In this approach, the effects of phenomena present in actual test conditions must be accounted for in laboratory tests so that potential errors associated with the testing environment are included. For these tests, direct comparison of the non-contacting measurements to independent measurements by established methods using documented ASTM procedures (see Practice E 83 and Test Methods E 251) whenever possible are recommended to obtain quantitative estimates of the accuracy of the Derived Data. If this approach is used, all data acquisition and analysis procedures must remain the same as used for actual tests, with clear documentation provided to demonstrate that the same procedure has been used for both tests.

6.5 *Non-contacting System Simulation*—It is emphasized that the evaluation of an optical measurement system under simulated experimental conditions cannot be used to obtain quantitative error measures. However, simulation can be a useful tool to (*1*) isolate the effects of different error sources as described in 5.2-5.7, (*2*) compare different data extraction procedures and (*3*) study the performance of the measurement method under conditions where no validated standard method is available for experimental comparison. By isolating the effects of different error sources, the critical parameters affecting the accuracy can be identified and improved experimental procedures can be developed. Comparison of different extraction procedures can be used to identify image-processing methods that are well suited for a particular application. Results from (*3*) can be used to identify situations where the experimental method is not suitable to obtain accurate data, even when improvements in the experimental procedure and image processing are implemented. As an example, an optical method might not be well suited to obtain accurate strain measurements in regions of large strain gradient (for example, near a crack tip or bi-material interface), which is difficult to verify experimentally. However, simulations can determine estimates for the accuracy achievable under such conditions.

6.5.1 Documentation of simulation studies should include all information necessary to independently verify the results. Typical documentation may include (*1*) a description of the physical models, (*2*) algorithms used for Basic Data generation and Derived Data extraction and (*3*) range of parameters considered in simulations.

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE

X1.1 A simple example is discussed in some detail to clarify the concepts outlined in this guide. First, Fig. X1.1 and Fig. X1.3 show the basic data. The basic data includes a two-dimensional array of intensity data before and after deformation. For the purpose of discussion, X is measured on the object and has dimension of physical length. The form shown in these figures is consistent with the recording of a fringe pattern (for example, moiré). However, the principles are similar for all optical methods (for example, speckle photography, white light speckle).

X1.2 A derived data quantity is the wavelength of the intensity pattern. Since the initial displacement field is zero, one may interpret the initial intensity field as having a wavelength $\lambda \to \infty$, resulting in the constant intensity field shown in Fig. X1.1.

X1.3 Fig. X1.2 shows a displacement field with constant strain, ϵ_o. To simplify the discussion, we will assume that the strain is proportional to the inverse of the optical intensity pattern wavelength. For this case, an optical pattern with wavelength, λ_o, will be observed as is shown in Fig. X1.3. If a displacement field such as the one shown in Fig. X1.4 occurs, the resulting intensity pattern will have the form shown in Fig. X1.5. A constant sampling interval, d_s, is shown in Fig. X1.5 so that sampling effects can be discussed.

X1.4 As shown in Fig. X1.5, the spatial wavelength will change with the underlying displacement field. From $0 \leq X \leq X_1$, the displacement field increases at constant slope ϵ_o and the spatial wavelength, λ_o, is constant. In the region $X_1 \leq X \leq X_2$, the displacement has an increased slope, ϵ_1, and the wavelength, λ_1, decreases. From $X_2 \leq X \leq X_3$, the displacement field has its smallest slope, ϵ_2, and the wavelength increases to λ_2. Finally, from $X_3 \leq X \leq X_4$, the slope of the displacement field increases to a maximum value, ϵ_{-1}, resulting in the shortest wavelength, λ_{-1}.

X1.5 Derived data would include measurement of quantities such as fringe spacing or wavelength in Fig. X1.3 and Fig. X1.5. The range of spatial wavelengths in the deformed pattern, $\lambda_{-1} \leq \lambda \leq \lambda_2$, corresponds to the spatial frequency range $\kappa_2 \leq \kappa \leq \kappa_{-1}$, where $\kappa = 2\pi/\lambda$. To obtain accurate fringe spacing, the optical resolution of the lens system must be OR $\leq \lambda_{-1}$. With sufficient optical resolution, sampling with a spacing, d_s, results in the highest spatial frequency that can be measured without aliasing, $\kappa_s = \pi/d_s$. Using these definitions, the optical data bandwidth is independent of the optical intensity pattern and is given by the range $0 \to \kappa_s$. The recording resolution is $\kappa = 1/d_s$. The spatial resolution for the optical data is the reciprocal of the recording resolution and is given by $\kappa^{-1} = d_s$. Regarding the process of decoding intensity data to estimate the underlying displacement field shown in Fig. X1.4, the Fourier transform of the intensity pattern provides a simple method for conceptualizing the key issues. Fig. X1.6 shows a typical Fourier transform for intensity patterns such as shown in Fig. X1.4, where F{} is the square of the amplitude and X is spatial frequency.

X1.6 As shown in Fig. X1.6, information in the frequency range $\kappa > \kappa_s$ is aliased near the DC component in the Fourier domain. This corresponds to an intensity pattern that is under-sampled, resulting in a loss of spatial frequency information. Thus, it is not possible to reconstruct the underlying displacement field in this portion of the intensity pattern. Information in the frequency range $\kappa_2 \leq \kappa \leq \kappa_s$ of the intensity pattern can be approximated with reasonable accuracy, so that the underlying displacement field can be approximately reconstructed. The accuracy of the reconstruction for the displacement field will depend upon many factors (for example, quantization effects, noise in intensity pattern, interpolation method). A detailed discussion of how these affect the accuracy of the displacement field is not within the scope of this guide.

X1.7 To determine the dynamic range for the encoded

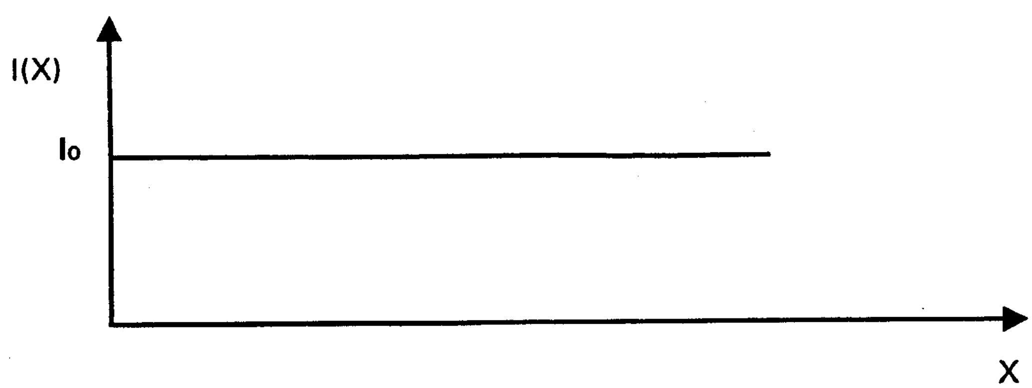

FIG. X1.1 Constant Intensity Pattern Prior to Deformation

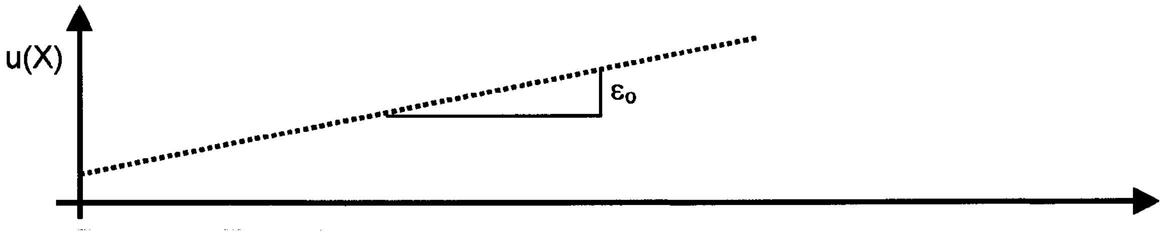

FIG. X1.2 Linearly Varying Displacement Field with Slope ϵ_o.

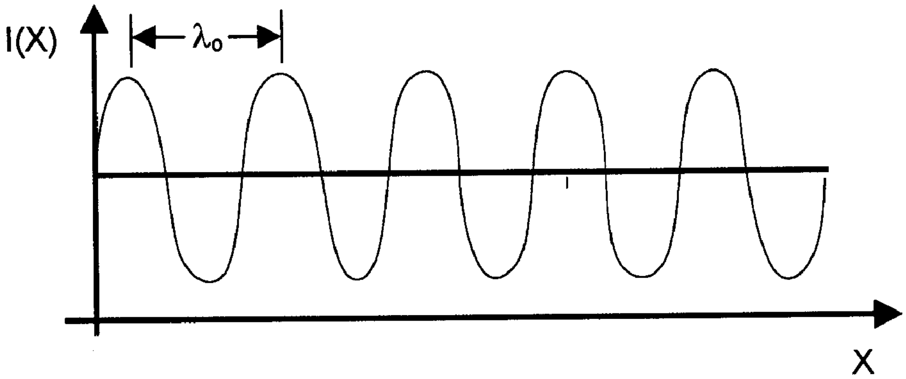

FIG. X1.3 Intensity Pattern After Application of u(X) with Strain ϵ_0

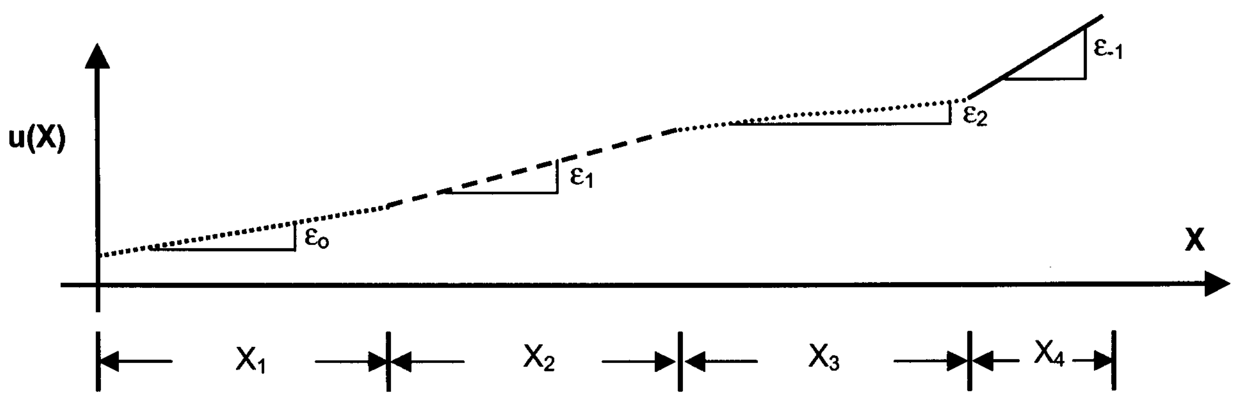

FIG. X1.4 Displacement Field with Four Ranges of Constant Strain

information, a functional relationship between the underlying displacement field and the intensity field variations is required. The one suggested earlier is a reciprocal relationship between the local displacement field and the wavelength of the resulting optical pattern. For this case, $\lambda^{-1} = C\,\epsilon$, where ϵ is the underlying strain or gradient of displacement. Hence, an expression for the dynamic range of the underlying strain field can be written $(2\pi C)^{-1}\kappa_2 \leq \epsilon \leq (2\pi C)^{-1}\,\kappa_s$.

X1.8 Determination of the encoded data bandwidth will depend on the method of image analysis used to extract the information and is not discussed in detail in this Appendix. As an example, smoothing operations are performed on the data in many signal-processing applications. Smoothing will attenuate the high frequency content of the signal, thereby reducing the spatial resolution and bandwidth of the encoded information. Furthermore, the spatial resolution may not be "fixed" for a given method, but will depend upon how the measurement method is implemented. One example of how implementation will affect spatial resolution is the choice of subset size in digital image correlation; increasing the subset size will reduce spatial resolution when extracting the underlying displacement field.

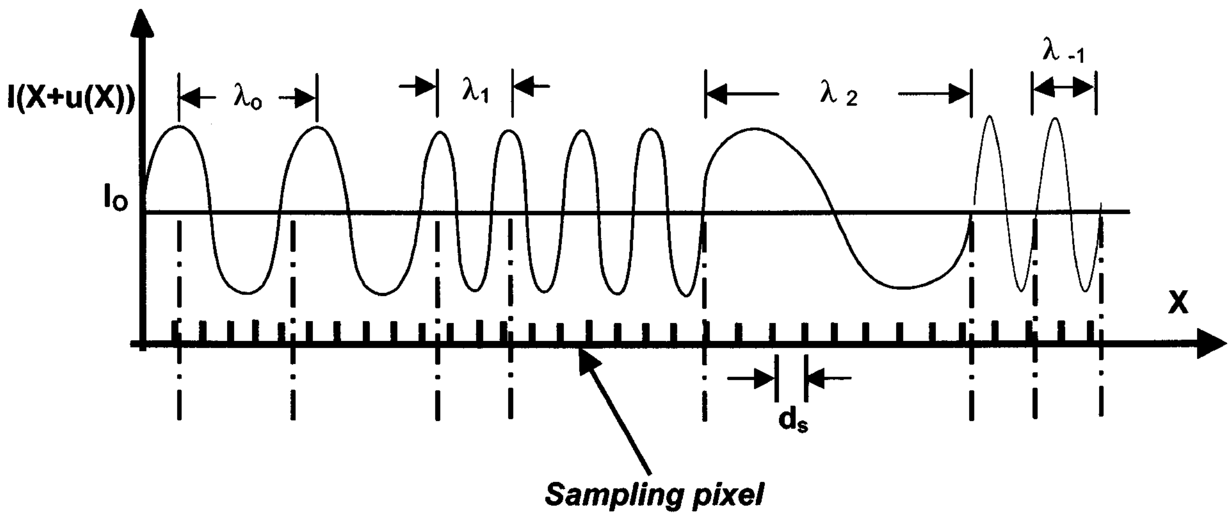

FIG. X1.5 Intensity Field Observed After Application of Variable Displacement Field

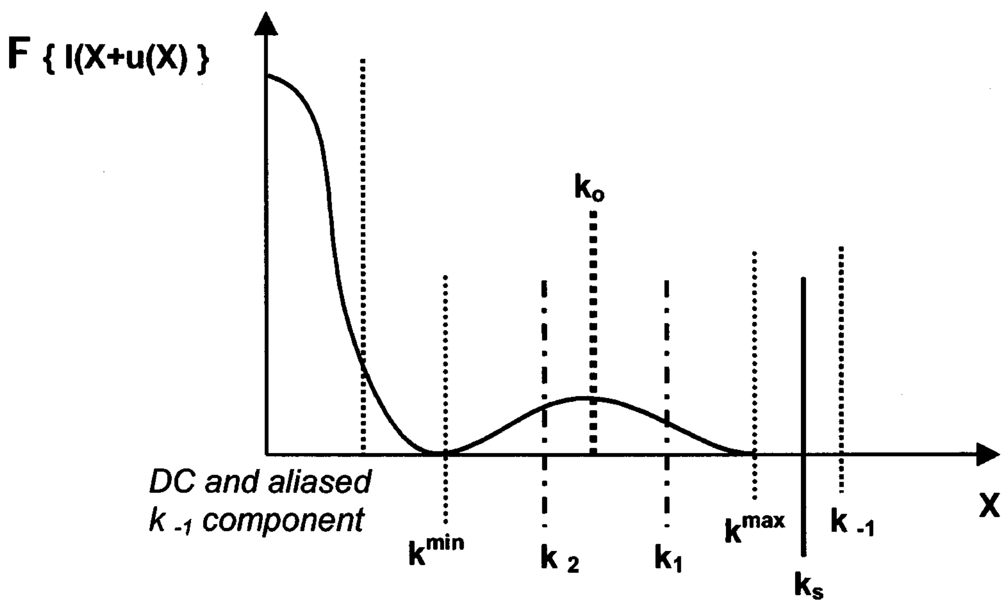

FIG. X1.6 Fourier Transform of the Deformed Intensity Pattern