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ASTM Letterhead

Date: 1 May 2000

To: ASTM Subcommittee 08.03 Members
"Advanced Apparatus and Test Methods"

From: Pete McKeighan
Co-chairman, Task Group 08.03.03 (Sensor Technology)

Re: **Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems**

Based upon a discussion and vote at last Fall's meeting, the intent of the subcommittee was to ballot the above referenced Standard Guide in preparation for June's meeting. In the meantime the document has undergone a significant revision, including for instance a number of graphical descriptions of the processes involved. The timetable of this revision was such that the deadline for ballot items was missed.

Consequently, what we would like to do at this June's meeting is again review this document, in preparation of imminent balloting. To make this process easier, the draft Standard Guide is attached for review. Please review in preparation of the 1 PM task group meeting on Monday, June 12. If you have issues but are unable to attend, please forward them to the following individual:

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Response to comments

1. Scanning laser systems are not strain measurement systems. Typically, they measure the shape of an object. Since the original standard was to be directed towards non-contacting strain measurement systems, scanning laser systems are not included at this time.
2. Two camera issues are not included, as no discussion of a specific method was intended in the draft standard.
3. Bandwidth definitions have been added to the terminology section.
4. A short discussion regarding normal strain measurements and the effects of displacement measurement errors has been added to provide more concrete examples of how the Standard Guide would be applied.
5. A general definition of Measurement Resolution has been provided in the terminology section, which is applicable for both strain and displacement.
6. Quasi-static has been removed and a sentence added to ensure that all discussions are restricted to measurement of events that occur slowly relative to the integration time of the optical medium. After much discussion, it seems clear to us that the inclusion of a detailed discussion of dynamic effects will require much more care and the addition of at least one person with a strong background in high-speed studies.
7. Deformation was added at one place in the Scope section.
8. References to these standards were added.
9. Not sure why these are needed in a draft standard guide. It is intended as a general set of guidelines for optical methods, not as a primer on how optical systems may appear in applications. However, schematics of both moire' and digital image correlation setups are given for reference purposes.
10. Several terms added.

11, Coherent and incoherent illumination added to terminology. Use described only obliquely.

12. Use for large structures has been eliminated. Focus is still broad in scope, but not restricted to large or small structures. Application to fatigue/fracture is not emphasized, but clearly within scope of Standard Guide.
13. Note regarding these issues is included in the guide.
14. Short notes regarding minimization of errors are included where appropriate.
15. The calibration section has been reworded.

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Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems

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1. SCOPE

The purpose of this document is to assist potential users in understanding the issues related to the accuracy of non-contacting strain measurement 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 (i.e., 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. TERMINOLOGY

Optical data: Recorded images of specimen, containing encoded information related to the displacement and/or displacement gradient field.

Decoded data: Measurement information related to the displacement or displacement gradient field.

Optical data bandwidth: Spatial frequency range of the optical pattern (e.g. fringes, speckle pattern, etc.) that can be recorded in the images without aliasing or loss of information.

Optical resolution (pixels/length), k: Number of optical sensor elements (pixels) used to record an image of a region of length L on object.

Spatial resolution for optical data: One-half of the period of the highest frequency component contained in the frequency band of the encoded data.

Decoded data bandwidth: Spatial frequency range of the information after decoding of the optical data

Dynamic range: The range of physical parameter values for which measurements can be acquired with the measurement system.

Spatial resolution for encoded data: One-half of the period of the highest frequency component contained in the frequency band of the decoded data.

Coherent illumination: Light source where the difference in phase is solely a function of optical path differences; interference is a direct consequence.

Incoherent illumination: Light source with random variations in optical path differences; constructive or destructive interference of waves is not possible.

Maximum temporal frequency of encoded data: Reciprocal of the shortest event time contained in the encoded data (e.g., time variations in displacement field)

Quantization level: Number of bits used in the 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.*

Optical integration time: Time over which digital image data is averaged to obtain a discretely sampled representation of the object.

Measurement resolution: Smallest change in the physical property that can be reliably measured.

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.

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.

Accuracy: Quantitative relationship of the measurements to the value obtained by standard measurement techniques

Basic data: Data obtained directly by the measurement system. For optical, non-contacting methods, image data is generally the basic data.

Derived data: Data obtained through processing of the basic data. Typically, this is displacement field data.

3. DESCRIPTION OF GENERAL OPTICAL NON-CONTACTING STRAIN MEASUREMENT SYSTEMS

Figures 1 and 2 show schematics of typical moire' 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 Standard 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 E-8 for tensile testing of metals [1] or E-399 for plane strain fracture toughness [2,3] provide the basis for (b, c).

4. ERROR SOURCES

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 Standard Guide.

4.1 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 (e.g., analog or digital), camera spatial resolution, data acquisition board type, pixel quantization level (e.g., 8 bits), ratio of pixel dimensions, lens type and manufacturer. When photographic film is used to record images, the film characteristics as well as lens type and manufacturer used in imaging should be documented.

4.2 Errors due to extraneous vibrations

Depending upon the measurement resolution, system vibrations can increase errors in (a) extracting encoded information and (b) the actual encoded information. 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.

4.3 Errors due to lighting variations

Since the Basic Data is image data, lighting variations during the experiment may affect (a) the actual encoded information (e.g., phase shift in coherent methods) and (b) 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 (e.g., normalized cross correlation) will increase the accuracy of the extracted data.

4.4 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 (e.g. high density moiré' interferometry).

4.5 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 (e.g. 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.

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

$$\varepsilon_{nn} = (L_n^{final} - L_n^{initial}) / L_n^{initial}$$

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 (a) errors in the initial length of the line element and (b) 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.

4.6 Errors in processing extracted data

Errors are introduced when the form of extracted Derived Data in Section 4.5 is processed to obtain strain data. This process can involve a wide range of mathematical operations including (a) numerical differentiation of derived displacement data and (b) smoothing of displacement or displacement gradient data. Errors introduced by the choice of post-processing method can include, but are not limited to, (a) reduction of spatial resolution, (b) systematic under-prediction of strain in areas of high strain gradients, (c) phase errors in the signal due to non-symmetric operators etc.

5. CALIBRATION PROCESS

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 Standard Guide will not address specific details involving the application of any technique. Rather, the guidelines are provided as a general framework for calibration of non-contacting optical strain measurement systems.

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, ASTM standard methods [4,5] 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 (a) the accuracy of local variations observed in the Derived Data or (b) the accuracy of the Derived Data in regions outside the area where comparisons were made.

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

$$E\varepsilon_{nn} \cong \Delta L_n^{\,final} / L_n^{\,initial}$$

Here, $\Delta L_n^{\,final}$ 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.

5.1 Comparison to standard measurement methods for similar test conditions

Non-contacting measurements can be made under diverse conditions (e.g., high temperature, in-situ structures, laboratory test frames, vacuum). Due to the diversity of conditions, calibration tests performed on similar components under similar conditions are recommended. 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.

For these tests, direct comparison of the non-contacting measurements to independent measurements by established methods using documented ASTM procedures (e.g., extensometers [4], strain gages [5]) 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 used in the calibration test must remain the same for actual tests, with clear documentation provided to demonstrate that the same procedure has been used for both tests.

5.2 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 performed on laboratory specimens are recommended. 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 [4,5] 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 used in calibration tests must remain the same for actual tests, with clear documentation provided to demonstrate that the same procedure has been used for both tests.

5.3 Non-contacting system simulation

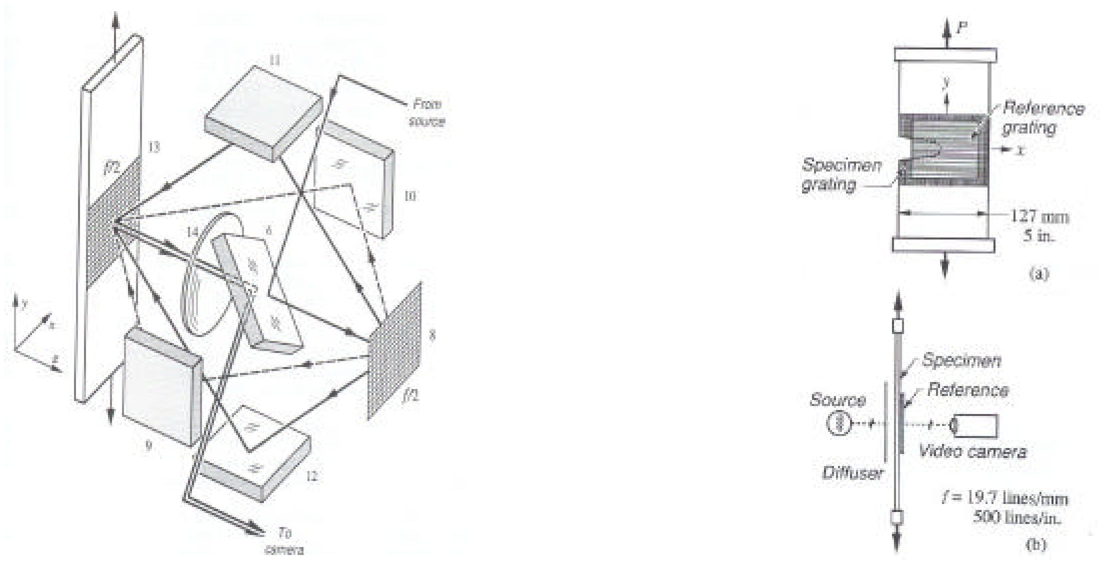
It is emphasized that the evaluation of an optical measurement system under simulated experimental conditions cannot be used to obtain quantitative error measures. However, simulation can be a useful tool to (a) isolate the effects of different error sources as described in 4.1-4.6, (b) compare different data extraction procedures and (c) 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 (c) 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 (e.g. 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.

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

6. Referenced Standards:

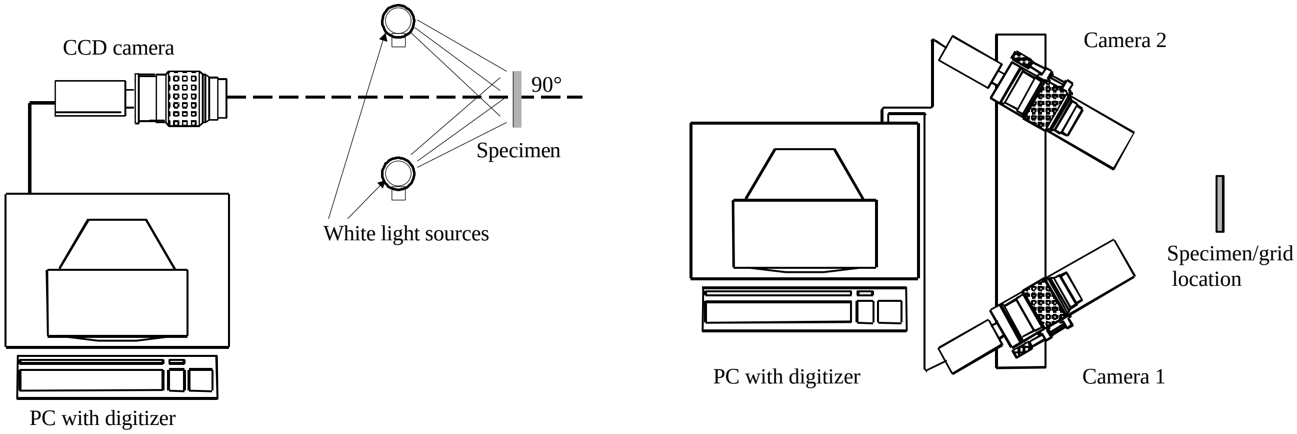
1. E 8-99 Test Methods for Tension Testing of Metallic Materials; Volume 03.01 Metals-Mechanical Testing; Elevated and Low Temperature Testing; Metallography
2. E 399-90 (1997) Test Method for Plane Strain Fracture Toughness of Metals; Volume 03.01 Metals-Mechanical Testing; Elevated and Low Temperature Testing; Metallography
3. E 1823-96 Terminology Relating to Fatigue and Fracture Testing, Volume 03.01, Metals-Mechanical Testing; Elevated and Low Temperature Testing; Metallography.
4. E 83-98 Standard Practice for Verification and Classification of Extensometers, Volume 03.01 Metals-Mechanical Testing; Elevated and Low Temperature Testing; Metallography.

5. E 251-92 (1998) Test Methods for Performance Characteristic of Bonded Resistance Strain Gages; Volume 03.01 Metals-Mechanical Testing; Elevated and Low Temperature Testing; Metallography.



(a) Compact moire inteferometer *(b) Moire with white light*

Figure 1: Typical optical moire' systems for in-plane displacement measurement



(a) 2-D Digital image correlation setup *(b) 3-D Digital image correlation setup*

Figure 2: Typical digital image correlation setups for (a) in-plane displacement measurement and (b) three-dimensional displacement measurement

Appendix

A simple example is discussed in some detail to clarify the concepts outlined in the Standard Guide. First, Figure A-1 and A-3 show the **basic data.** The **basic data** includes an intensity field 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 (e.g. moire'). However, the principles are similar for all optical methods (e.g., speckle photography, white light speckle).

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 $\lambda \rightarrow \infty$, resulting in the constant intensity field shown in Figure A-1.

Figure A-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 Figure A-3. If a displacement field such as the one shown in Figure A-4 occurs, the resulting intensity pattern will have the form shown in Figure A-5. A constant sampling interval, d_s, is shown in Figure A-5 so that sampling effects can be discussed.

As shown in Figure A-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 lowest 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 lowest wavelength, $\lambda_{-1.}$

Derived data would include measurement of quantities such as fringe spacing or wavelength in Figures A-3 and A-5. The range of spatial wavelengths in the deformed pattern, $\lambda_{-1} \leq \lambda \leq \lambda_2$, corresponds to the spatial frequency range $k_{-1} \leq k \leq k_2$, where $k = 2\pi/\lambda_.$ Sampling with a spacing, d_s, results in the highest spatial frequency that can be measured without aliasing, k_s. = π/d_s. Using these definitions, the **optical data bandwidth** is independent of the optical intensity pattern and is given by the range $0 \rightarrow k_s$. The **optical resolution** is $\kappa = 1/d_s$. The **spatial resolution for the optical data** is the reciprocal of the optical resolution and is given by $\kappa^{-1} = d_s$. Regarding the process of decoding intensity data to estimate the underlying displacement field shown in Figure A-4, the Fourier transform of the intensity pattern provides a simple method for conceptualizing the key issues. Figure A- 6 shows a typical Fourier transform for intensity patterns such as shown in Fig. A-4.

As shown in Figure A-6, information in the frequency range $k > k_s$ 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 $k_{-1} \leq k \leq k_s$ 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 (e.g., 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 Standard Guide.

To determine the **dynamic range** for the encoded 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, $\lambda^{-1} = C\,\varepsilon_,$ 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 $(2\pi C)^{-1} k_{-1} \leq \varepsilon \leq (2\pi C)^{-1} k_s$.

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.

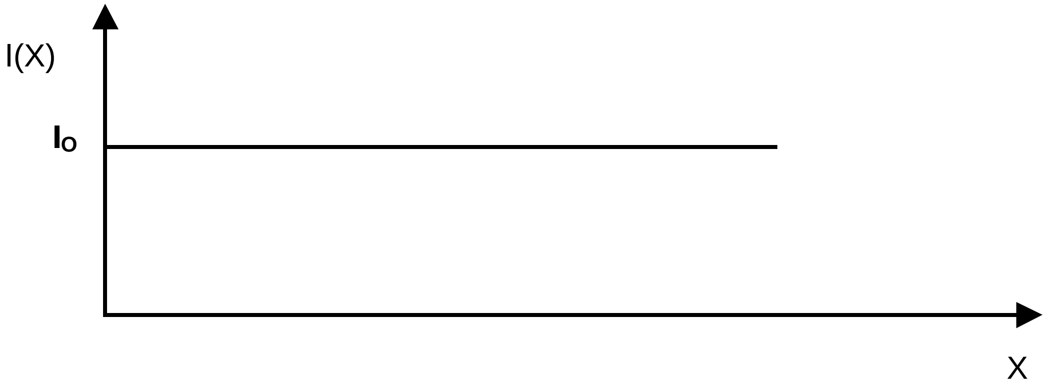


Figure A-1: Constant intensity pattern prior to deformation

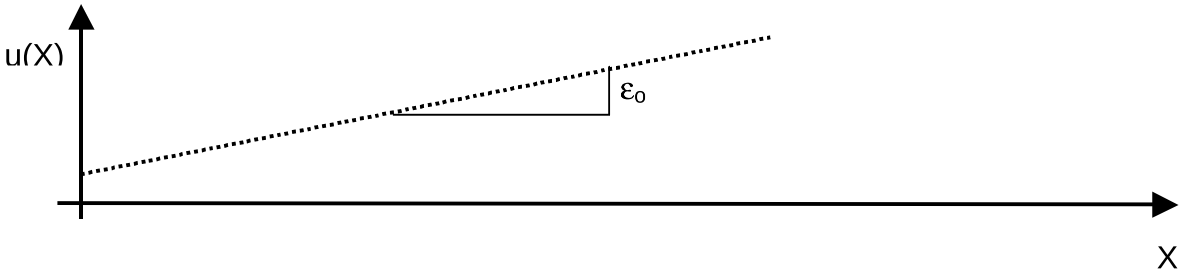


Figure A-2: Linearly varying displacement field with slope ε_o

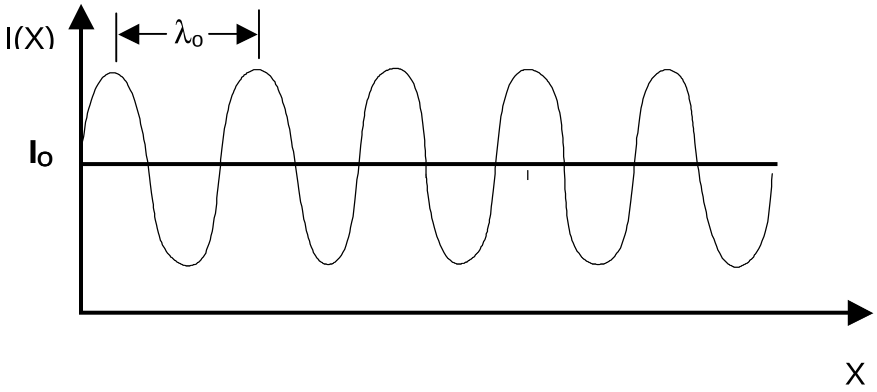


Figure A-3: Intensity pattern after application of u(X)

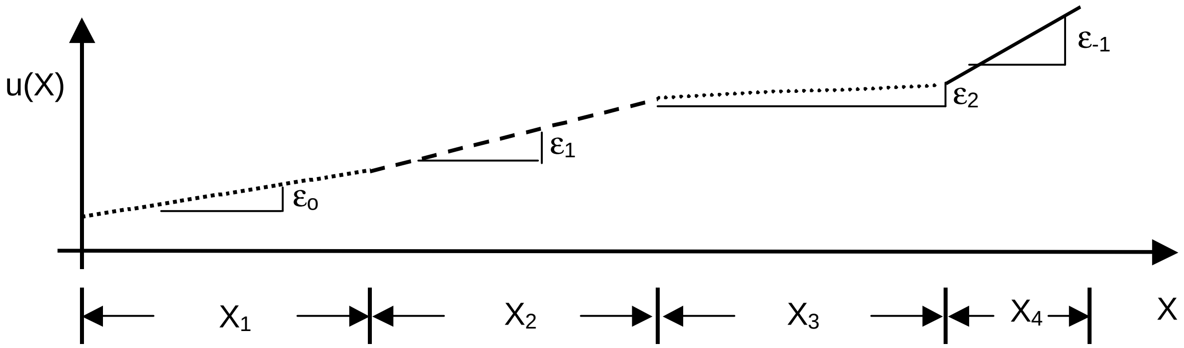


Figure A-4: Displacement field with four ranges of constant strain

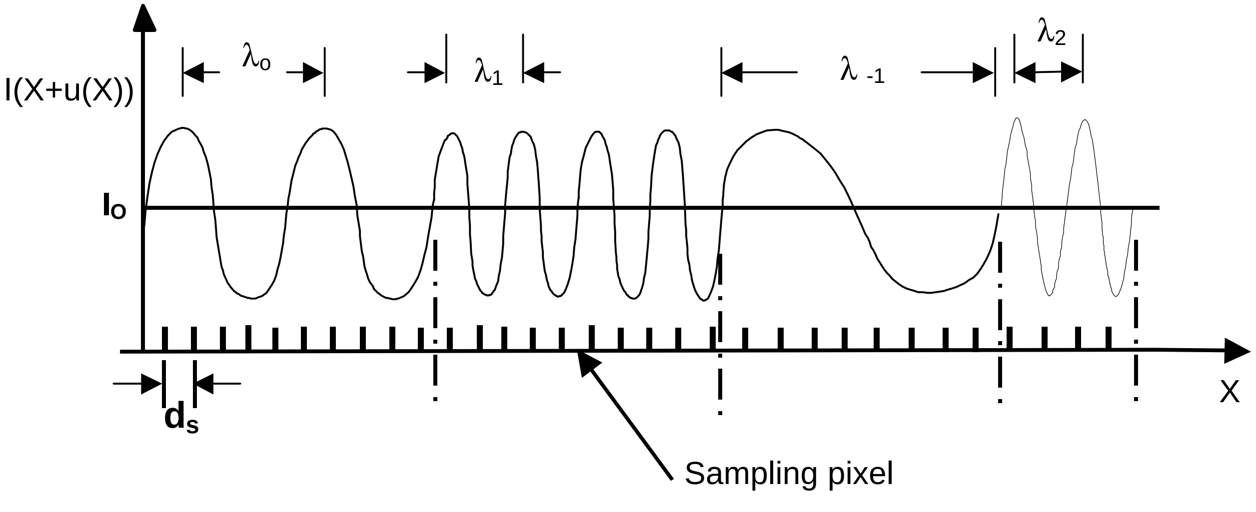


Figure A-5: Intensity field observed after application of variable displacement field

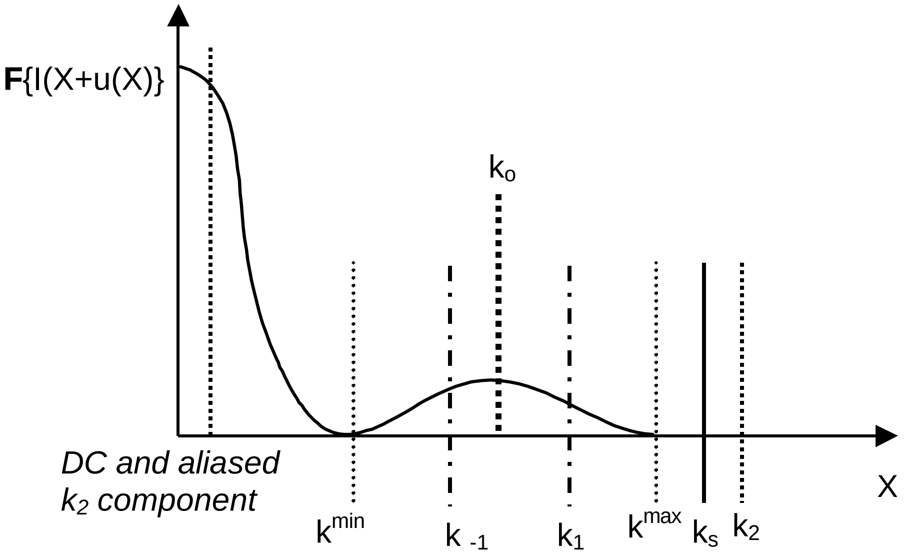


Figure A-6 Fourier transform of the deformed intensity pattern