

TRACEABILITY, REFERENCE MATERIALS AND STANDARDISED TESTS IN OPTICAL STRAIN MEASUREMENT

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ABSTRACT

Imaging methods are applied in engineering and experimental mechanics areas to measure strain fields. The SPOTS project tackles the problem of traceability in optical strain measurement. Strain, being a displacement derivative, is a measurement quantity derived from the base unit length. We outline routes for traceability of optical strain measurement values, and underline the role of measurement standards for strain. Measurement uncertainty for calibration of an ESPI interferometer is detailed.

1. INTRODUCTION

Strain, being a displacement derivative, is a measurement quantity derived from the base unit length. It is therefore natural but not mandatory to trace strain values back to displacement values and hence to the base unit of length. In a common tensile test strain is approximated by the average unit elongation in the direction of the applied force, determined from total elongation ΔL of a selected gauge length L_0 by

$$\varepsilon = \frac{\Delta L}{L_0} \quad (1)$$

In the simple one-dimensional case of Eq. (1) traceability of the strain measurement results is established by calibrating the devices for measuring elongation and gauge length against a reference standard for the unit of length such as a laser interferometer or vernier calliper. In contrast, strain calibration is hardly performed even for the simple resistive strain gauge. Most users assume that the k-values given by the manufacturers are correct, and calibration procedures are mostly limited to the amplifier stage, e.g. by using bridge calibrators.

This need for knowing strain fields in many engineering and experimental mechanics areas has encouraged the application of imaging methods for strain measurement. Since every free external surface of a body is a principal plane on which the normal principal stress is zero. Planar strain states on the surface are described by the two-dimensional tensor

$$\begin{pmatrix} \frac{\partial u}{\partial x} & \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) & \frac{\partial v}{\partial y} \end{pmatrix} = \begin{pmatrix} \varepsilon_x & \varepsilon_{xy} \\ \varepsilon_{xy} & \varepsilon_y \end{pmatrix} \quad (2)$$

Full-field techniques provide position resolved strain values $\varepsilon_i(x,y)$, and in some cases $\varepsilon(z)$. They require special attention, as they can have position dependent calibration and uncertainty values. Some well-known optical techniques are speckle and holographic interferometry, shearography, grating moiré, image correlation, and photoelasticity [1]. Some of them measure the surface deformation state $\mathbf{v} = (u,v,w)$ by acquiring primary measurands, e.g. intensity. Others acquire measurands directly proportional to strain components. All use model concepts of the measurement procedure to calculate strain. Table 1 gives an overview of some methods and the involved quantities.

Table.1: Measurement principles of optical methods for strain measurement..

Method	Primary measurand	Strain measurement principle
Speckle / holographic interferometry	Displacement induced change of optical path measured by interferometric intensity modulation	Strain calculated from the displacement field
Shearography	Strain induced change of optical path between sheared surface points measured by interferometric intensity modulation	Primary measurand directly proportional to strain component in optical shearing direction
Grating interferometry / moiré	Displacement induced change of grid constant measured by interferometry or transmission intensity modulation	Strain calculated from the displacement field
Image correlation	Displacement induced change of position of optical feature in the image	Strain calculated from the displacement field
Photoelasticity	Strain induced birefringence measured by intensity or color modulation	Primary measurand directly proportional to difference of principal strains

The quality of the data generated is strongly dependent on the procedures and model concepts employed as well as set-up of the instrumentation. Thus, there is a significant need to provide standards both for procedures and instrumentation in order to provide traceability of strain values, to present technical comparability to users and to promote the compatibility of systems. This brought together national laboratories, industrial and academic partners in the SPOTS-project in order to develop appropriate reference materials for strain [2]

2. TRACEABILITY AND VALIDATION

The laboratory accreditation standard ISO 17025 [3] requires measurement values to be traceable. A similar requirement is stated in ISO 10012 [4]. Traceability is not a meaningful end in itself, but is a component of a quality assurance system. According to VIM 6.10 [5], traceability is the *”property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties”*. In practice, traceability of a measurement value is established by a hierarchy of calibrations to a primary or national standard (*”traceability chain”*) [6]. The concept of primary standard is equally valid for base quantities and derived quantities, e.g. length and strain respectively.

While, in general, calibration is performed for a few selected values of the measurand only, performance assessment can include property values that correspond closely to the objects

normally under test, and therefore can be used for validation and adjustment purposes [7]. Hence there is a two-fold need for strain standards: standards used for establishing traceability and standards used for validation of measurement procedures. Figure 1 shows the role of standards in traceability and validation.

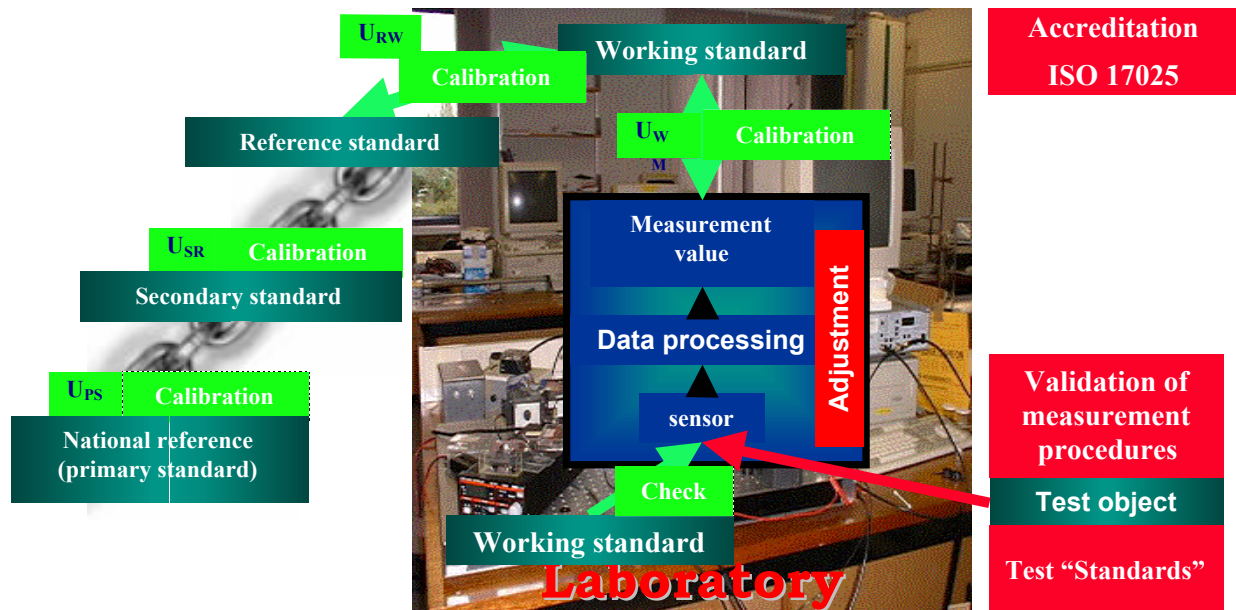


Fig.1: Traceability chain, the use of standards and the relation to validation and accreditation. To each calibration step from standard A to B, an expanded uncertainty U_{AB} is associated.

How to establish traceability?

- Define the measured quantity
- Document the measurement process, system and working standard
- State the measurement result and its uncertainty
- Use the measurement system and the references or standards according to “internal measurement assurance”
- Describe the unbroken chain of comparisons to the national standard, including uncertainties at each step

In view of the very different optical techniques compiled in Table 1, there is no simple way of comparing measurement systems. For every method and instrument the measurement chain from the test object to the measurement value has to be considered, based on the model assumptions made. But, like in the tensile test, Eq. (1), and the strain gauge calibration mentioned above there is no direct link from the strain of the object to the measurement result. Rather, calibration is performed using the testing equipment in the laboratory itself.

The traceability pathway down the hierarchy of standards can be a long one, as suggested in Figure 1. The longer the path, the more uncertainties are compounded. It may be assumed that calibration laboratories down the chain know about the measurement uncertainties involved in the position of their links. Therefore, here we focus on the first member of the chain, the link of the measurement value to the working standard. By defining intrinsic standards, and a measurement assurance system in place for using them properly and evaluating the results of using them, the path can be short, direct and immediate. Hence, traceability could be appreciably simplified if an object with known strain values were available: a reference material for strain.

3. REFERENCE MATERIAL AND ROUTES FOR TRACEABILITY

A Reference Material (RM) has by definition [8] *property values that are sufficiently homogeneous and well established to be used for the calibration of an apparatus, or the assessment of a measurement method*, both of which are important issues, as outlined above. Because strain is not a material property in a strict sense, we will use in the following the term "Measurement standard", defined as a *material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference* [5].

A device intended to reproduce or supply, in a permanent manner during its use, one or more known values of a given quantity (a so-called Material measure), for strain shall be developed within the SPOTS project. Candidate reference materials are described in a second paper in this session [9]. Since most optical methods mentioned so far do not measure residual strain but difference in strain, e.g. the transition from an unstrained to a strained state of the object, the reference material must be devised to reproducibly repeat the strain states. And more, it must represent a strain field that is adapted to the imaging property of the techniques. As mentioned above, traceability of strain measurement values by using devices for length and displacement measurement seems a natural choice. It might be mentioned, however, that electrostrictive materials could be used to trace back to the voltage normal using the voltage-strain relation. Alternatively one might also think of thermal expansion of a calibration body, and tracing back to the temperature scale.

In other fields, such as NDT, standards are provided that focus on applicability of optical methods rather than calibration. Hence, these standards can be used for validation purposes, sometimes in a qualitative rather than quantitative manner. They usually come in the form of a test piece with artificial defects of various sizes in order to assess the applicability of an optical method. Sometimes not a test piece, but a catalogue of signatures of typical defects is compiled, which is compared to the actual measurement result in order to identify the type of defect.

ASTM F1364 describes a straining block for assessment of interferometric nondestructive tire inspection systems [10]. Essentially it is an underpressure loaded rubber membrane in contact with a block featuring a series of circular holes. The performance of shearographic or holographic interferometric measurement systems can be tested against this straining block.

BRITE-EuRAM programme BE5145 was concerned with the development of improved in-service inspection methods for safety-critical aircraft structures [11]. To that end, a validation of present in-service inspection techniques, to understand their reliability and limitations had been performed. A catalogue of typical defect responses to shearography applied on aerospace components has been compiled.

A similar catalogue for shearographic tube testing is presented in the German standard DIN V 54180-3:1997-03 [12]. Fringe phase patterns for a selection of defect type and tube parameters are given.

4. CALIBRATION OF AN ESPI INTERFEROMETER

4.1 Modeling the measurement

In this section we sketch the traceability procedure for a 3-D Electronic Speckle Pattern Interferometric (ESPI) measurement system. ESPI has become popular as a tool for sub-micrometer resolution deformation measurements in qualification, FEM validation and non-destructive testing. When used for quantitative investigations as e.g. for FEM validation, care must be taken in extracting properly calibrated values from the recorded phase fringe patterns. The main uncertainties arise from incomplete knowledge of system and test parameters.

Therefore, the nanometer resolution of an interferometric technique may not be misinterpreted as the measurement uncertainty determined in accordance with GUM [13]. Figure 2 shows the process of an ESPI measurement, together with the influence parameters and measurement uncertainties. This is an example of the generic process of optical strain measurement that is discussed in another paper [14]. The change in the object light path due to a deformation $\mathbf{v}(\mathbf{x})$ is usually expressed as a phase change and approximated by

$$\Delta\Phi(\mathbf{x}) = \mathbf{v} \cdot \mathbf{s} \quad (3)$$

with the sensitivity vector defined as

$$\mathbf{s} = \frac{2\pi}{\lambda} \left(\frac{\mathbf{x} - \mathbf{Z}}{|\mathbf{x} - \mathbf{Z}|} + \frac{\mathbf{x} - \mathbf{B}}{|\mathbf{x} - \mathbf{B}|} \right) \quad (4)$$

For three different illumination directions \mathbf{s}_i , $i = 1 \dots 3$, we obtain three different phase differences due to the same deformation, which is in matrix notation

$$\Delta\Phi(\mathbf{x}) = \mathbf{S}\mathbf{v} \quad (5)$$

from which the displacement is obtained by inversion. It is well known that in a general ESPI set-up the sensitivity matrix is not diagonal, not even in so called out-of-plane or in-plane set-ups. In case the off-diagonal elements are neglected, this systematic effect must be quantified. In reality, the measured phase difference is not given by the object deformation alone but by other effects like thermal wavelength change (due to n -variation), illumination and observation centre displacements, rigid body motion as well as reference path changes. We therefore introduce a correction term \mathbf{e} :

$$\Delta\Phi(\mathbf{x}) = \mathbf{S}(\mathbf{x})\mathbf{v}(\mathbf{x}) + \mathbf{e}(\mathbf{x}) \quad (6)$$

4.2 Input quantities

There are several input and influence quantities affecting the measurement uncertainty, as listed in Fig.2. Some of them have been discussed in the literature, e.g. [15], but a detailed treatment is beyond the scope of this paper. It is usually not reasonable to quantify each and every contribution and to modularly add them. Sometimes, they can be simulated and numerically assessed. If a correction is not possible, the contribution must be treated as a measurement uncertainty [13].

Sensitivity matrix

We assume that the sensitivity matrix is properly taken into account and only uncertainty of its components will contribute to the measurement uncertainty. These are mainly caused by the measurement uncertainty of the geometry (object shape, distance, angles, position of illumination, finite lens aperture, pixel area on object).

Rigid body displacement

Since interest is in object deformation, all rigid body displacements, i.e. translation and rotation, must be eliminated. This correction introduces an uncertainty depending on to which extent the parameters of rigid body motion are known. An important effect can be due to the thermal elongation of the measurement head, object, and supports.

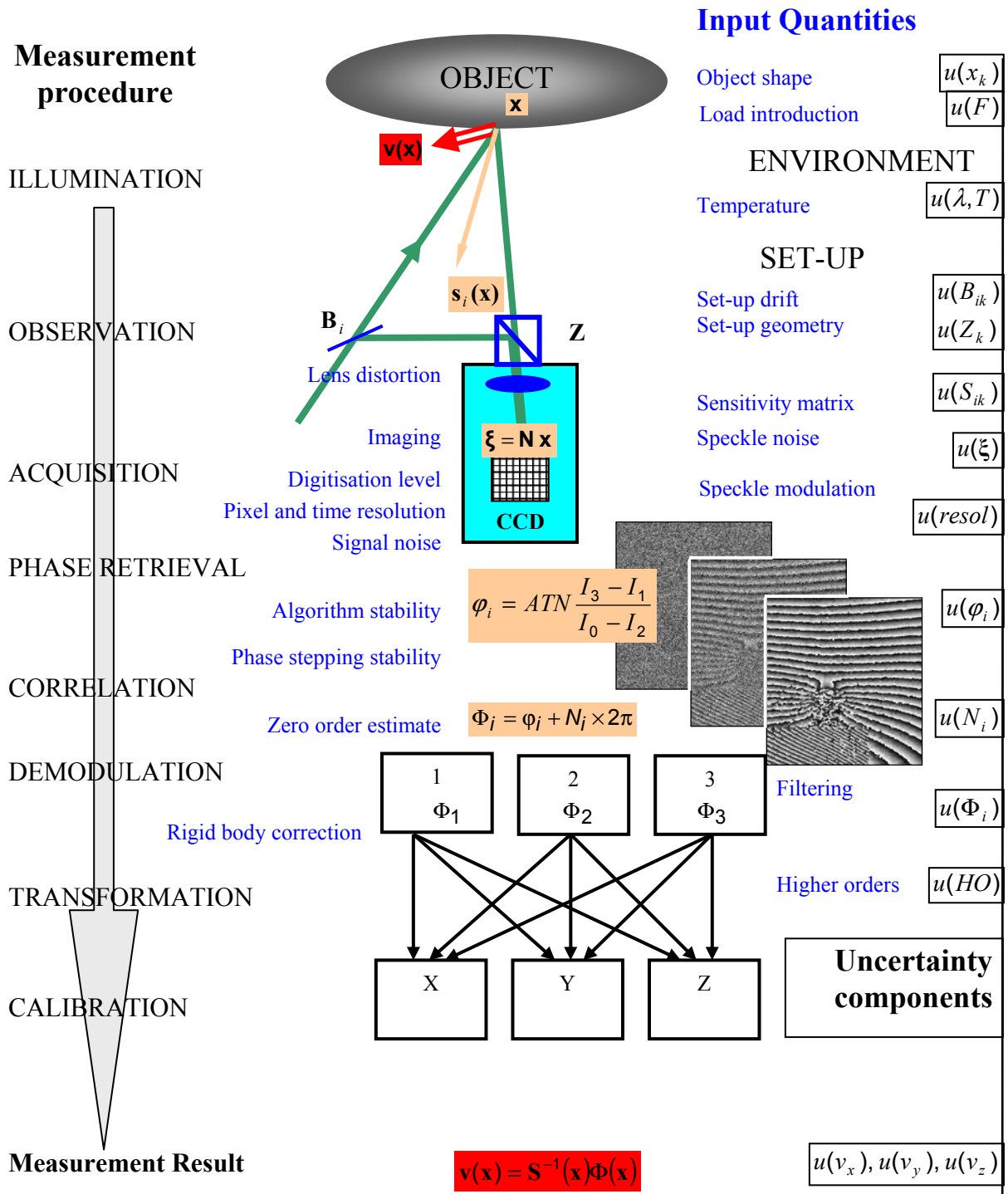


Fig.2: Steps, parameters and uncertainties involved in ESPI-deformation analysis.

Absolute fringe order

Since the phase map is measured modulo 2π (fringe field), the exact location of zero order is unknown. It may be outside the image. Therefore, the absolute fringe order N must be included:

$$\Delta\Phi(\mathbf{x}) = \Delta\varphi(\mathbf{x}) + N \times 2\pi \quad (7)$$

Phase determination

There has been a lot of interest in phase step procedures in the literature. Phase stepping is performed based on capturing a number of images with a phase step induced between them in order to extract the phase values of the optical (object) path. Uncertainty sources are phase step miscalibration and non-linearities, quantization levels, type of algorithm, and higher harmonics. Because the uncertainty due to phase stepping is mostly restricted to a fraction of a fringe, it is important in optical shop testing, but much less so in ESPI strain measurements. Here, in general, influences of the test set-up as listed below are dominant. The uncertainty in phase measurement, $u(\varphi)$, also includes speckle noise and A/D conversion of the video signal, i.e. finite quantisation levels of (poor) speckle phase modulation. Adding up several load steps gives a maximum uncertainty (uncorrelated addition) of \sqrt{n} times the single measurement value.

Set-up stability

Stability effects comprise thermal wavelength change, source stability (e.g. pointing stability), displacement of illumination source points as well as drifts in the reference phase.

Field of view

Measurement uncertainties can explicitly or implicitly depend on the position within the field of view (FOV). Examples are variation of magnification or fringe modulation across the FOV.

4.3 Calibration uncertainty

The procedure described above leads to the complete result of the ESPI measurement, i.e. deformation values $\mathbf{v}(\mathbf{x})$ together with the expanded uncertainty $U(\mathbf{v})$. Basically, if a pixelwise algorithm has been used to perform the phase calculation, each pixel represents a measurement value and the uncertainty is referred to this point-wise measurement. If the measurand of interest is not a point but, e.g. a local average or a gradient, the measurement uncertainty must be propagated according to the rules of error propagation.

When a measurement standard is used as the object, the deviation of the measurement result from the value realized in the standard can be compared to the measurement uncertainty to check the plausibility of the latter. In turn, part of the measurement uncertainty can be assessed globally by this comparison, when it is possible to vary in a controlled manner the influence parameters.

Note that the measurement standard itself has an uncertainty associated to the realized strain values. The calibration uncertainty for this first member of the traceability chain is given by the combined standard uncertainty of the measurement and the reference values.

5. CONCLUSION

It is necessary to establish traceability of strain values obtained with optical techniques in order to obtain reliable, quantitative results for engineering applications. The first step is to provide a generic reference standard for strain values that can be applied to different measurement techniques. After successful termination of the SPOTS project, the measurement standard will be used to establish traceability, together with the measurement uncertainty at each step of the calibration chain.

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ACKNOWLEDGEMENT

The work presented forms part of the SPOTS project (G6RD-CT-2002-00856) which is funded through the GROWTH programme of the European Union and by the Swiss Federal Office for Education and Science (BBW).