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Calibration and validation of full-field techniques

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Abstract. We review basic metrological terms related to the use of measurement equipment for verification of numerical model calculations. We address three challenges that are faced when performing measurements in experimental mechanics with optical techniques: the calibration of a measuring instrument that (i) measures strain values, (ii) provides full-field data, and (iii) is dynamic.

1 Vocabulary and Definitions

Working with engineering people from around the world we have noticed a lack of awareness regarding some basic concepts of measurement techniques. While much effort has been undertaken to promote the idea of measurement uncertainty in the last decade, confusion is still around when talking about traceability, calibration or validation, or the discussion is considered as being relevant to calibration laboratories only, but not the test bench of the practicing engineer.

We will briefly remind the reader of the commonly accepted definitions as given by the *Vocabulaire International de métrologie* (VIM – International Vocabulary of Metrology) [1]. We will then apply the basic concepts and their implications on reference materials and their use. We focus on three challenges that are faced when performing measurements in experimental mechanics with optical methods: how to calibrate a measuring instrument that (i) measures strain values, (ii) provides full-field data, and (iii) is dynamic.

1.1 Traceability

VIM (2.41) defines traceability or more properly "metrological traceability" as "the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." For this definition, a 'reference' can be a definition of a measurement unit through its practical realization, or a measurement procedure including the measurement unit for a non-ordinal quantity, or a measurement standard. Metrological traceability requires an established calibration hierarchy which is called a metrological traceability chain. The ILAC (International Laboratory Accreditation Cooperation) considers the elements for confirming metrological traceability to be (i) an unbroken metrological traceability chain to a national or international measurement standard (ii) a documented

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measurement uncertainty (iii) a documented measurement procedure (iv) accredited technical competence (v) metrological traceability to the SI, and (vi) calibration intervals [2].

1.2 Calibration

VIM (2.39) defines calibration as the "operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication." Often, the first step alone in this definition is perceived as being calibration.

1.3 Validation

VIM (2.44, 2.45) defines validation as "provision of objective evidence that a given item is adequate for an intended use". Hence, validation prevents the use of a measurement system which is inappropriate for the intended use although it might be calibrated. Adequateness of a strain measurement system for use in experimental mechanics involves e.g. the appropriateness for the strain level that is expected, for the necessary spatial resolution, the measurement rate, etc.

2 Challenges

2.1 Challenge 1: Traceability to the SI

It is commonly accepted that the traceability chain should link to a primary standard, i.e. a realization of a unit within the SI (*Système International d'Unités)*. While this is a straightforward process for deformation and displacement measurements which are naturally linked to the unit of length *meter*, it is less obvious how the measurement result of a derived quantity such as *strain* can be made traceable. In order to realize a measurement standard for strain, we recall VIM (5.1) which defines a measurement standard (or etalon) to be a "realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference." Such a "realization of the definition of a given quantity" can be provided by a measuring system, a material measure, or a reference material. VIM (5.1) defines reference material (RM) as a "material, sufficiently homogeneous and stable with reference to specified properties, which has been established to be fit for its intended use in measurement or in examination of nominal properties." Since these definitions do not detail the nature of the quantity to be realized, it applies to derived quantities as well.

It necessitates a model system to realize the derived quantity that must be controlled by input quantities for which the traceability chain is established and from which the derived quantity to be calibrated is calculated. If a simple analytic relation between input and (derived) reference value exists, the traceability is straightforward again. Considering strain, the use of the measurement of a base length L and an elongation $\Delta\ell$ is viable, eq.(1) – and indeed popularly used in tensile testing – because both measurements can be traced back to the length scale and the unit *meter*.

$$\varepsilon = \Delta\ell / L \qquad (1)$$

However, other possibilities of realization of the unit strain can be envisaged [3]. The combined measurement uncertainty for the strain value is calculated from the uncertainties of the input quantities (L and $\Delta\ell$ in this simple case) and influence quantities (such as temperature, digital resolution, etc.) following the GUM [4].

2.2 Challenge 2: Full-field techniques

When calibrating an instrument, most often a single reference quantity is captured by a single transducer and compared to its reading. Figure 1 shows a typical calibration curve for an LVDT that is calibrated with a laser interferometer which serves as the traceable reference standard. The residual deviations from a linear function are reproducible within the random variations and hence could be corrected for. However, normally a single uncertainty value (or specification limit) is extracted from the graph, i.e. deviations are smaller than 0.01 mm across the entire range of values.

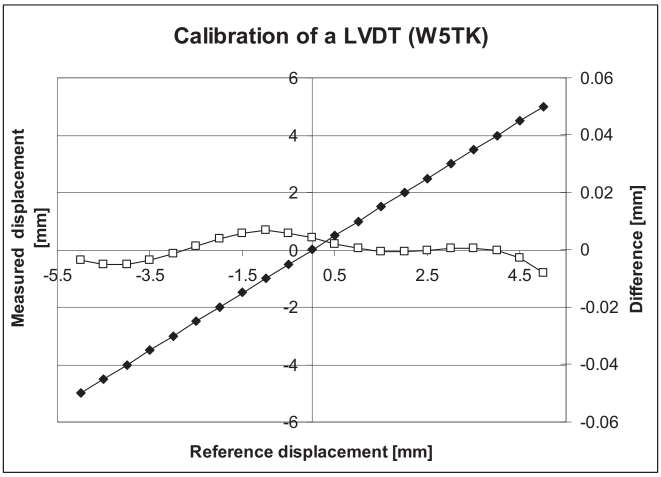
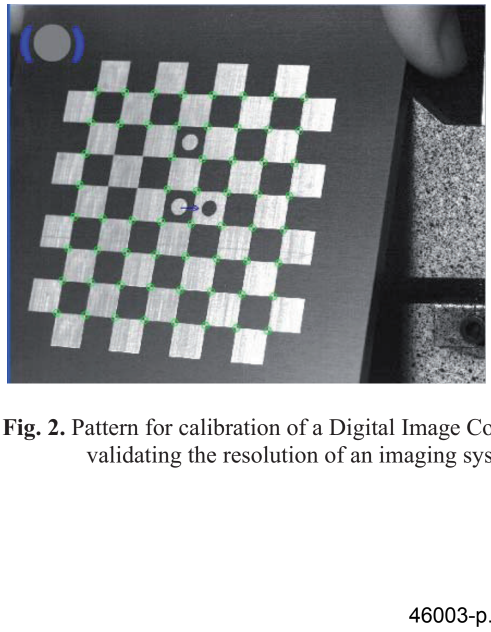


Fig. 1. Calibration curve of an LVDT and its residual deviations from a linear calibration function.

But how can a full-field technique be calibrated? And how should the measurement uncertainty be expressed in this case? Obviously, a field of reference values must be provided to calibrate a full-field technique. For camera calibration a well-known method is based on the use of a calibration plate. The calibration procedure provides the values of intrinsic and extrinsic parameters that are used to model the camera's imaging properties and to subsequently correct the images in order to obtain reliable coordinates of an object surface. In Digital Image Correlation such a camera calibration using specially designed chequerboard patterns is common use (Fig.2) [5].



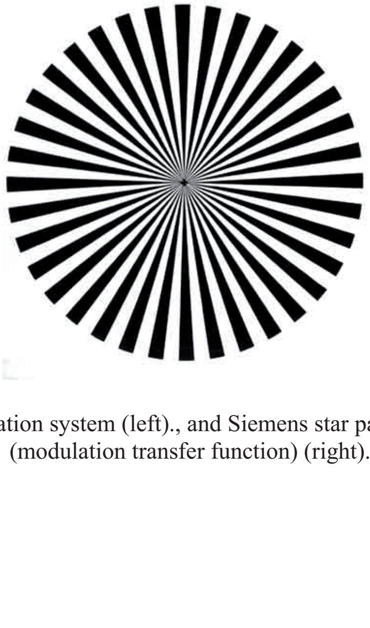


Fig. 2. Pattern for calibration of a Digital Image Correlation system (left)., and Siemens star pattern for validating the resolution of an imaging system (modulation transfer function) (right).

In contrast to the calibration of the imaging properties (aberrations) for measuring coordinates in space, embodiments with representative line patterns (USAF target, Siemens star) for validation of imaging systems, have been around for decades (Fig.2). They allow the assessment of the limitation of an imaging system and therefore are needed to define the applicability of the system, which is related to validation rather than calibration.

Similarly, for a full-field technique that measures a quantity different from surface coordinates, the need arises for an artefact that allows a full-field calibration of the quantity in question. As an example, specimens with artificial flaws are used to validate imaging or scanning NDE techniques. The requirements for such an artefact from the point of view of traceability of strain measurement, its realization for planar strain states and its use for calibrating an optical instrument is described elsewhere [6,7]. Basically, the strain field can be expressed as

$$\varepsilon(x, y) = \Delta\ell \times f(x, y) \tag{2}$$

where $\Delta\ell$ is again a (single) measured displacement value which is traceable, and $f(x, y)$ is an analytic function that describes the distribution of the strain values on the surface of the (planar) reference material. Calibration now involves not only the comparison of the values of the reference material and the measurement but also the identification of corresponding locations (x, y) which is a pre-requisite for a point-by-point comparison. The level of uncertainty with which this step can be performed adds to the calibration uncertainty. Figure 3 gives a full-field equivalent for the linear calibration of Fig.1. The simulated system is measuring out-of-plane displacement. For an array detector the calibration field has to be provided simultaneously and not sequentially as in Fig. 1. In this example, a linear variation of displacement along the y-direction, but no variation along the x-direction is introduced which corresponds to a simple tilt of a reference plane.

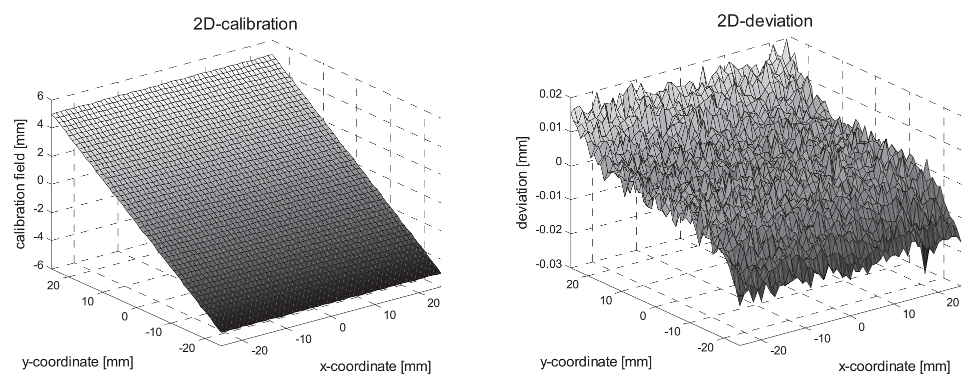


Fig. 3. Full-field equivalent to Fig.1 (simulated data). Calibration curve of a 2D-displacement measurement (left) and its residual deviations from the calibration values (right).

2.3 Challenge 3: Dynamic measurements

A final challenge to be mentioned is to overcome the limitations of a static calibration in order to calibrate instruments for dynamic measurements of displacement or strain. This challenge adds still another degree of freedom to the calibration process: the time. Motivation of this extension is the use of optical measurement systems for dynamic events. Dynamic events, from vibrations to impact, are especially important in the transportation industry. In the 7th Framework Programme of the European Union a collaborative project was started to tackle this challenge [8]. ADVISE is a pre-normative project for experimental validation of simulations of dynamic events using full-field optical methods of deformation measurement. ADVISE brought together nine partners from across Europe and the United States. Although in engineering modelling the analysis of homogeneous materials subject to impact has become fairly routine, an experimental validation of the numerical results is still needed. However, since impact testing is a cost intensive venture, the replacement of actual experimental testing by reliable, validated simulations is a goal of many developers. Recent advances in material technology allow the use of light-weight but still impact-resistant fibre reinforced polymers. Modelling the impact of two-dimensional composites and three-dimensional analysis is under development. Therefore, there is a need to bring together optical techniques with the developments in modelling composites in order to accelerate the latter and establish high levels of confidence through rigorous validation. The objectives of the ADVISE project are:

- development of reference materials that allow traceability and calibration of full-field optical methods of deformation measurement in cyclic, transient and non-linear dynamic events;
- optimisation of methodologies for both optical measurement and computational modelling and simulation of non-linear, transient dynamic events;
- contributions to standardisation activity for experimental validation of dynamic simulations.

Extending eq. (2) to the simplest dynamic case, a periodic deformation, reads as follows:

$$\varepsilon(x, y, t) = \Delta\ell \times f(x, y) \times \cos(\omega t + \varphi) \tag{3}$$

where now $\Delta\ell$ is a (single) measured displacement value (an amplitude) which is traceable, $f(x, y)$ is an analytic function that describes the distribution of the strain or displacement values on the surface of the reference material, and $\cos(\omega t + \varphi)$ describes the time evolution of the measurement values.

3 Measurement uncertainty

While the calibration steps have been described above, there remains the question of how to express the measurement uncertainty in the case of full-field data. To be specific, we consider measurement data that are taken by an array of pixel elements such as that from a CCD camera (cf. Fig.3). At first sight, there are two extreme positions that could be taken:

- Every pixel of the camera is treated as a single sensor, and hence, every value of the pixel array has its individually calculated measurement uncertainty.
- A global measurement uncertainty is stated for the entire measurement system.

In most cases, a global estimate of the measurement uncertainty is too coarse, while a detailed pixel-by-pixel analysis is not manageable. The former is useful if only average measurement results from the imaging system are reported, while the latter is necessary, if measurement values of single (or a few) pixels are reported in the application, e.g. when a very localised peak load is measured. In practice, a set of equations that describes the dependence of the measurement uncertainty both on the signal level as well as its variation across the field of view proves most useful. Although such a parameterization can sometimes be backed up with physical significance, the identification of individual components from the residuals is not unique. The example in Fig.3 contains a random component, i.e. additive noise for each pixel, but also overall deviations, i.e. systematic components. Depending on the application of the imaging system and the maximum allowable uncertainty level, the systematic components can be (partially) corrected for or be included in the expression of the measurement uncertainty. The example of Fig.3 has an average standard deviation of 0.0022 mm along the lines in x-direction, but an average standard deviation of 0.0066 mm along the lines in y-direction as well as for the entire array of data.

4 Conclusion

We have discussed the needs for calibration and validation of imaging measurement systems in view of three challenges: derived quantity, full-field data, and dynamic data. It is the requirement of the application that defines the levels of accuracy for calibration and the validation of the system. Equally, the measurement uncertainty must be expressed in a way that is appropriate for the intended use.

Acknowledgement

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