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Radiography-based mechanical identification

C. Jailin[1], A. Buljac[1,2], A. Bouterf[1], F. Hild[1], S. Roux[1]

1 – LMT (ENS Paris-Saclay/CNRS/Univ. Paris-Saclay), 61 avenue du Président Wilson, 94235 Cachan, France
2 – MINES ParisTech, PSL Research University, Centre des Matériaux, CNRS UMR 7633, BP 87, 91003 Evry, France

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Abstract — A recently developed Projection-based Digital Image Correlation (P-DVC) method is here extended to 4D (space and time) displacement field measurement and mechanical identification based on a single radiograph per loading step instead of volumes as in standard DVC methods. Two levels of data reductions are exploited, namely, reduction of the data acquisition (and time) by a factor of 1000 and reduction of the solution space by exploiting model reduction techniques. The analysis of a tensile elastoplastic test composed of 127 loading steps performed in 6 minutes is presented. The 4D displacement field as well as the elasto-plastic constitutive law are identified.
Keywords — Image-based identification, Model reduction, Fast 4D identification

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Introduction The identification and validation of increasingly complex mechanical models is a major concern in experimental solid mechanics. The recent development of computed tomography coupled with *in-situ* mechanical tests and full field measurements offers the opportunity to identify kinematic and/or mechanical quantities on the tested sample. The 4D frameworks [1] based on a series of 3D scans (each composed of approximately 1000 radiographs requiring 1 hour scan time in lab-CT) at different loading steps have proved to be very efficient but extremely time intensive (and in turn fragile with respect to slow drifts). These approaches are thus often limited to few scans and forbid time dependent mechanical characterizations.

A recently developed Projection-based Digital Volume Correlation (P-DVC) [2] overcomes these difficulties by extracting the measured quantities directly from few radiographs instead of reconstructed volumes. The technique was originally developed for crack characterization in synchrotron or lab-CT [3] by using only two orthogonal projection angles per step resulting in a gain of 300 in acquisition time compared with the classical full scan method. P-DVC is herein extended to elastoplastic identification from a single projection per loading step. The proposed method allows *on-the-fly* radiograph acquisitions to be carried out while continuously loading and rotating the sample with an additional improvement of more than 2 in the acquisition time.

P-DVC is based on the minimization of the quadratic difference between the projection of the deformed sample acquired at angle $\theta(t)$, $g(\boldsymbol{r},t)$, and the computed projection of the reference 3D image, $\widetilde{F}(\boldsymbol{x})$ corrected by a trial displacement field, $\boldsymbol{u}(\boldsymbol{x},t)$, $\widetilde{F}_{\boldsymbol{u}}(\boldsymbol{x}) = F(\boldsymbol{x}-\boldsymbol{u}(\boldsymbol{x},t))$. Denoting $\Pi_{\theta(t)}$ the projection operator in the orientation $\theta(t)$, the P-DVC functional reads

$$\chi^2[\boldsymbol{u}] = \sum_{\boldsymbol{r},t} (\Pi_{\theta(t)}[F(\boldsymbol{x}-\boldsymbol{u}(\boldsymbol{x},t))] - g(\boldsymbol{r},t))^2 \tag{1}$$

Spatio-temporal framework The displacement field is expressed on a spatio-temporal basis composed of the dyadic products of temporal $\phi_i(t)$ functions (e.g., generic forms such as polynomials, splines, or based on other time signals such as angle or force measurement) and spatial fields $\boldsymbol{\psi}_j(\boldsymbol{x})$ (finite element shape functions). A full measurement, which is composed of all combinations of space and time fields would be computationaly costly if the total number of degrees of freedom is significant. Hence, a PGD framework [4, 5] is used herein to successively enrich the displacement field with the dominant mode that is identified to reduce the current residual. Each of these modes consists of the product of one space field and one time function. Hence the displacement field at iteration n is written as

$$\boldsymbol{u}^n(\boldsymbol{x},t) = \boldsymbol{u}^{n-1}(\boldsymbol{x},t) + \left(\sum_{i=1}^{N_t} a_i^n \phi_i(t)\right) \left(\sum_{j=1}^{N_s} b_j^n \boldsymbol{\psi}_j(\boldsymbol{x})\right). \tag{2}$$

The mode enrichment of the PGD method is stopped when a criterion on the decrease of the P-DVC functional is reached. The residual fields (i.e., difference $(\Pi_\theta[\widetilde{F}_{\boldsymbol{u}}] - g)$ whose quadratic norm has been minimized in Eq. (1)) provide both a local and global quantifier of the trustworthiness of the measurement procedure.

Application to a mechanical test A tensile test on a dog bone cast iron sample is performed *in situ* until failure. The entire test is composed of 127 projections acquired in 2.5 turns for a total time of 6 minutes. Because the specimen is slender, the basis spatial fields are rigid body displacements of 15 cross sections distributed normal to the sample axis and linearly interpolated along the sample axis. The time basis is composed of 7 simple polynomial functions.

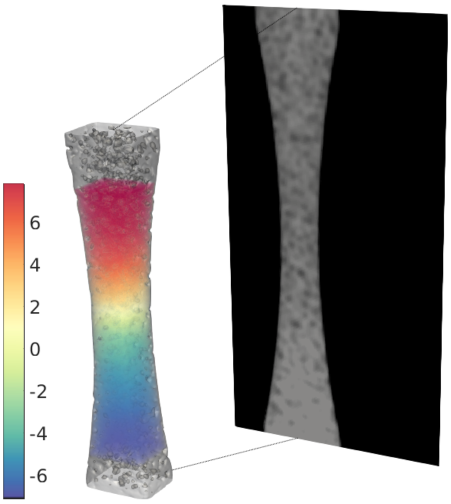

Figure 1: Schematic of the proposed approach, where the projection (background) is matched to the computed projection of the reference volume (front) deformed by the actual color-coded axial displacement just before failure (the displacement is expressed in voxels, 1 voxel ≡ 10.7 µm)

At convergence, the measured displacement field is composed of 8 rigid body motion modes and 4 deformation modes. When compared to the $6 \times 15 \times 7 = 630$ potential degrees of freedom, the sparsity exploited by the PGD approach is obvious. The measured displacement can be used further to feed an inverse procedure to identify an elastoplastic law. Finally, a perspective to this work is to merge the constitutive law identification step with the proposed fast 4D PGD P-DVC procedure into a fully *"integrated"* approach.

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