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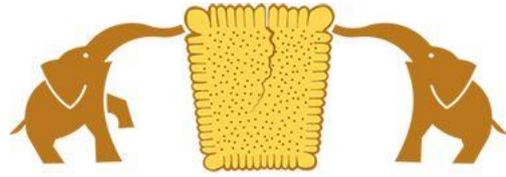
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Quantification of heat induced errors in stereo-DIC measurements during isothermal rigid body motion tests

Aniket Ghosh Dastidar⁽¹⁾, Abderrahmane Ayadi^{(1),*}, Marie-France Lacrampe⁽¹⁾

⁽¹⁾IMT Lille Douai, Institut Mines-Télécom, Univ. Lille, Centre for Materials and Processes, F-59000 Lille, France

*corresponding author : abderrahmane.ayadi@imt-lille-douai.fr

Abstract — Measuring kinematic fields using stereoscopic imaging is recurrent in the field of photomechanics, nevertheless, the heterogeneity of the refraction index of air along the optical path can become critical once such measurements are to be performed at relatively high temperatures. This study sheds more light on quantifying thermally induced errors in the case of the stereo-digital image correlation measurements (stereo-DIC) within the thermoforming temperatures range of thin thermoplastic sheets. A post-processing procedure is introduced to nullify thermally induced errors based on a series of isothermal rigid body displacements of the same speckled sample. Based on a segregation between bias and noise of errors, the experimental results provided statistical data which can be extrapolated to correct kinematic measurements conducted during the thermoforming process of thin thermoplastic sheets.

Keywords — Stereo-DIC, Thermal errors, Heat waves, Error quantification

Introduction — In experimental mechanics, understanding the sources of errors affecting the precision of displacement and strain fields and having the ability to filter them are two essential considerations to guarantee accurate measurements and avoid erroneous interpretations. Within this same logic, the use of contact-less optical techniques in photomechanics such as the stereo digital image correlation (stereo-DIC) should respect these same considerations when applied to characterize large deformation of materials under high processing temperatures [1]. Indeed, DIC uses information based on the deformation of contrasted black and white speckles (random patterns) applied to a sample surface to quantify the displacements and strains [2]. Stereo-DIC combines stereoscopic vision from at least two different observation angles of the speckled surface, and then an image correlation algorithm is used to extract kinematic fields from the recorded images of the deforming random black and white patterns with consideration of a reference undeformed state of the material. The potential advantages of such technique have already been proven to measure ... (state some cases with a few refs.). Extending the use the stereo-DIC in industrial environments such as the case of open mold thermoforming of thermoplastic sheets has already been investigated by numerous authors [3]. Nevertheless, numerous challenges still require more in depth investigation to elucidate the technological challenges related to the wide range of thermoforming parameters. In particular, notably thermally-induced errors, are known to manifest in the form of a mirage effect on the recorded stereoscopic images of observed hot surfaces. Such effect, can be attributed to the heterogeneity of the refractive index along the optical path with the observation field of the used cameras [4]. It arises from the convection of ambient air coming into direct contact with the hot surface of the pre-headed thermoplastic sheet. This convective effect is referred to as ‘heat waves’ [5]. In literature, numerous authors have proposed solutions to mitigate the errors caused by heat waves. For example, Jones and Reu successfully reported the use high pass temporal filters [5]. Ma *et al.* combined the use of a background oriented schlieren and temporal averaging of defined sets of recorded images to remove both the main and random shimmering distortions [4]. In the context of

the current study, isothermal rigid body motion tests conducted within a heating chamber were combined with stereo-DIC measurements conducted far from the heating chamber were used to generate heat wave distortions within the recorded images. Four temperatures ranging between 105 and 120 °C were conducted and were compared to reference test conducted at room temperature (25°C) to quantify thermal errors.

Methods — Statistically, errors can be categorized under two broad classes. Random errors (or noise) which refer to the lack of precision or inaccuracy of measurements and systematic errors (or bias) which in turn qualifies the inaccuracy of measurements with good precision. A glass fiber reinforced polyamide sample of a rectangular shape was chosen as its melting temperature exceed the one of standard HIPS (~100°C). The sample was speckled and then fixed from its top side to the mobile part of a tensile machine equipped with a thermal chamber (Zwick Roell) for conducting the rigid body motion tests. First, the heating chamber is sealed until reaching and stabilizing the sample's temperature at the target temperature. Then a small window loacate in the front door of the heating chamber is opened and simultaneously stereoscopic recording is striggered at an acquisition frequency of 5 frames/second. Post-processing the stereo-DIC images (DaVis, LaVision®) gives a full field displacement from each subset center. The statistical mean of these values in the region of interest defines the displacement value v_{DIC} for that time instance. The systematic error, denoted by R_{total} (in %) is defined according to eq.(1) as the relative error between with the imposed displacement recorded by the tensile machine v_{imp} and the corresponding component of the displacement vector computed based on the stereo-DIC software and denoted by v_{DIC} :

$$R_{total}(T, t) = \frac{v_{DIC}(T, t) - v_{imp}(t)}{v_{imp}(t)} \times 100 \quad (1)$$

The total error R_{total} is then decoupled according to eq. 2 into R_{RT} which is the error obtained from the reference room temperature test in the absence of any heating source affecting the optical path (pertaining to errors only due to image correlation), and $R_{thermal}$ which are induced exclusively due to thermal perturbations of the optical path of the stereoscopic cameras.

$$R_{total}(T, t) = R_{RT}(T_{RT}) + R_{thermal}(T, t) \quad (2)$$

Following the computation of the different errors, a correction polynomial function was defined based on the temporal evolution of the computed thermal errors $R_{thermal}(T, t)$ during the rigid body test duration. These correction functions were then applied to the raw stereoscopic data to rectify the thermal and the DIC bias errors. After this correction operation, a temporal filter is created by averaging the residual error from each subset center in the region of interest over time. This filtering operation is applied to remove the remaining noise and obtain the final corrected full field displacements.

Results — The results show the dependency of the bias and noise errors according to temperature. Four time instances after the start of motion (60s, 80s, 100s and 120s) have been chosen to provide a demonstration of the quantification procedure of the errors. Fig. (1a) shows the variation of the thermally induced bias errors $R_{thermal}(T, t)$ with time at different temperatures. Fig. (1b) shows the distribution of the residual errors for 120°C at 80s after opening of the heating chamber in its raw state, after heat correction and additionally after applying the temporal filter.

Discussion and Conclusion — A few conclusions can be drawn:

1. The level of thermal error ($R_{thermal}$) drops along with time for all temperatures (1.256% drop during the interval of 60s to 120s for the case of 120 °C) due to the fact that the temperature of the heated chamber drops as the ambient air cools down. The magnitude of $R_{thermal}$ which characterize the inaccuracy of measurements are of 1.807% at 120 °C and drop with temperature decrease to 0.603% at 105 °C, with respect to the same cooling duration of 60s after the opening the door of the heating chamber. Such result, confirms that more the turbulence or magnitude of heating waves within the optical field of the stereoscopic cameras, more is the magnitude of systematic errors even after a relatively extended duration after stopping the heating source.

2. The application of the temporal filter reduces the overall standard deviation and increases precision. The pixel population lying in the residual error range of (-0.1, 0.1) mm increases from 54.19 % in the raw measurements to 70.49 % post application of the filter at 80s after opening of chamber.

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