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Full-frame, high-speed 3D shape and deformation measurements using stereo-digital image correlation and a single color high-speed camera

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ABSTRACT

Full-frame, high-speed 3D shape and deformation measurement using stereo-digital image correlation (stereo-DIC) technique and a single high-speed color camera is proposed. With the aid of a skillfully designed pseudo stereo-imaging apparatus, color images of a test object surface, composed of blue and red channel images from two different optical paths, are recorded by a high-speed color CMOS camera. The recorded color images can be separated into red and blue channel sub-images using a simple but effective color crosstalk correction method. These separated blue and red channel sub-images are processed by regular stereo-DIC method to retrieve full-field 3D shape and deformation on the test object surface. Compared with existing two-camera high-speed stereo-DIC or four-mirror-adapter-assisted singe-camera high-speed stereo-DIC, the proposed single-camera high-speed stereo-DIC technique offers prominent advantages of full-frame measurements using a single high-speed camera but without sacrificing its spatial resolution. Two real experiments, including shape measurement of a curved surface and vibration measurement of a Chinese double-side drum, demonstrated the effectiveness and accuracy of the proposed technique.

1. Introduction

Originally established in 1993 by Luo PF et al. [1] and continually improved by a number of other researchers [2–7], stereo-digital image correlation (stereo-DIC) has evolved into a mature and practical optical technique for non-contact, full-field three-dimensional (3D) shape and deformation measurements. Due to its prominent advantages of simple optical arrangement, easy specimen preparation and low requirement on experimental environment, this powerful technique has received widespread acceptance and increasingly application in both academic and industrial communities. For instance, to meet the increasing demands on full-field high-speed 3D deformation measurements, high-speed stereo-DIC (HS-Stereo-DIC) technique [8–10] using two synchronized high-speed or ultra-high speed cameras has been developed and widely explored. The application of high-speed stereo-DIC has been reported in a large variety of issues, including full-field vibration measurements [11], measurements of deformation responses to explosive blast loading [12], experimental investigations of materials under shock wave or projectile impact [13] and determinations of mechanical properties of materials subjected to transient loadings [14].

It is worth noting that existing high-speed stereo-DIC systems were mostly established based on the use of two stringently synchronized high-speed cameras. However, the construction of these HS-Stereo-DIC systems are both expensive and complicate because of the use of two high-speed cameras as well as the hardware investment and technique involved in the stringent camera synchronization. Even worse, for ultra-high speed cameras with a frame rate up to millions frame per second (fps), the synchronization of these two cameras is particularly difficult or even unachievable due to their specific imaging mechanism [15]. In consideration of the cost and complexity involved in the conventional two-camera HS-stereo-DIC technique, HS-stereo-DIC using a single high-speed camera is undoubtedly highly desirable.

As a matter of fact, a few attempts have been devoted to the development and application of single-camera high-speed (SCHS) stereo-DIC technique, which merely uses a single high-speed camera. For instance, Besnard et al. [16] reported the characterization of 3D necking phenomena of a cylinder made of high-purity copper by using a single high-speed camera and DIC. The single-camera stereo imaging technique was realized by placing two planar mirrors in front of the object and then recording the virtual images in these two mirrors using

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a single high-speed camera. Pankow et al. [15] established a SCHS stereo-DIC system by combing a four-mirror adapter with DIC, and then successfully measured the out-of-plane deformation of an aluminum plate under a shock wave impact. Recently, the four-mirror-adapter-assisted SCHS stereo-DIC was used by the authors of this article to retrieve full-field 3D transient deformations of CFRP panels under impact loading [17], as well as full-field 3D vibration measurement [18]. With the aids of the properly arranged optical devices, the synchronization problem of two high-speed cameras can be automatically eliminated, enabling transient 3D deformation measurement through a single high-speed camera.

However, using these reported mirror-assisted SCHS stereo-DIC techniques [14–18], two views with different perspectives are separately imaged onto the two halves of the camera sensor. Thus merely less than half size of camera sensor is available for defining the region of interest (ROI), which means a substantial reduction in the spatial resolution in DIC measurement. Considering the fact that the resolution of a high-speed camera generally decreases with the increase of the frame rate, it is of great significance to develop a SCHS stereo-DIC technique, which not only can reduce hardware investment and eliminate precise synchronization problem, but also is able to make the most of the limited spatial resolution of the high-speed camera.

To address this challenge, here we propose a novel SCHS stereo-DIC technique for full-frame, high-speed 3D shape and deformation measurement. The novelty of the proposed technique exists in the skillfully designed pseudo stereo vision apparatus, with which color images of a test object surface, composed of blue and red channel images from two different optical paths, can be recorded by a high-speed color CMOS camera. The recorded color images can be separated into red and blue channel sub-images using a simple but effective color crosstalk correction method, and be further processed by using regular stereo-DIC method to retrieve full-field 3D shape and deformation on the object surface. The effectiveness and accuracy of the proposed technique are demonstrated by shape measurement of a bottle with varying diameters and 3D deformation measurement of a vibrating object.

2. Methods

2.1. Optical arrangement

Fig. 1 schematically shows the optical arrangement of the proposed pseudo stereo-DIC system using a single color high-speed camera. The established system consists of a single color high-speed camera, a beam splitter prism placed before the camera lens, two optical bandpass filters with specific center wavelengths attached on the left and front of the beam splitter prism, and three planar mirrors (denoted as M_1, M_2 and M_3) arranged on the two optical paths. By adjusting the posing angles of the planar mirrors, the mirrors project the left (blue channel) and right (red channel) images of the stereo pair onto the imaging sensor of the high-speed camera, yielding the equivalent of two virtual high-speed cameras with converging axes. As a result, an overlapped color image of a test object surface composed of one blue and one red color views is captured. The color images recorded at different configuration can be separated into red and blue channel sub-images, which correspond to the left and right images recorded by two virtual high-speed cameras. These separated images can be processed by regular stereo-DIC to retrieve the full-field 3D shape and deformation. It is clear that the proposed approach allows the left and right images to overlap each other in one image, which means the spatial resolution of the camera sensor can be fully utilized. This constitutes the primary advantage over existing single-camera stereo-DIC techniques using a four-mirror adapter [19].

2.2. Color crosstalk correction

As described above, to realize full-frame, high-speed 3D deformation measurement, a color high-speed camera is required. However, to our best knowledge, commercially available color high-speed cameras

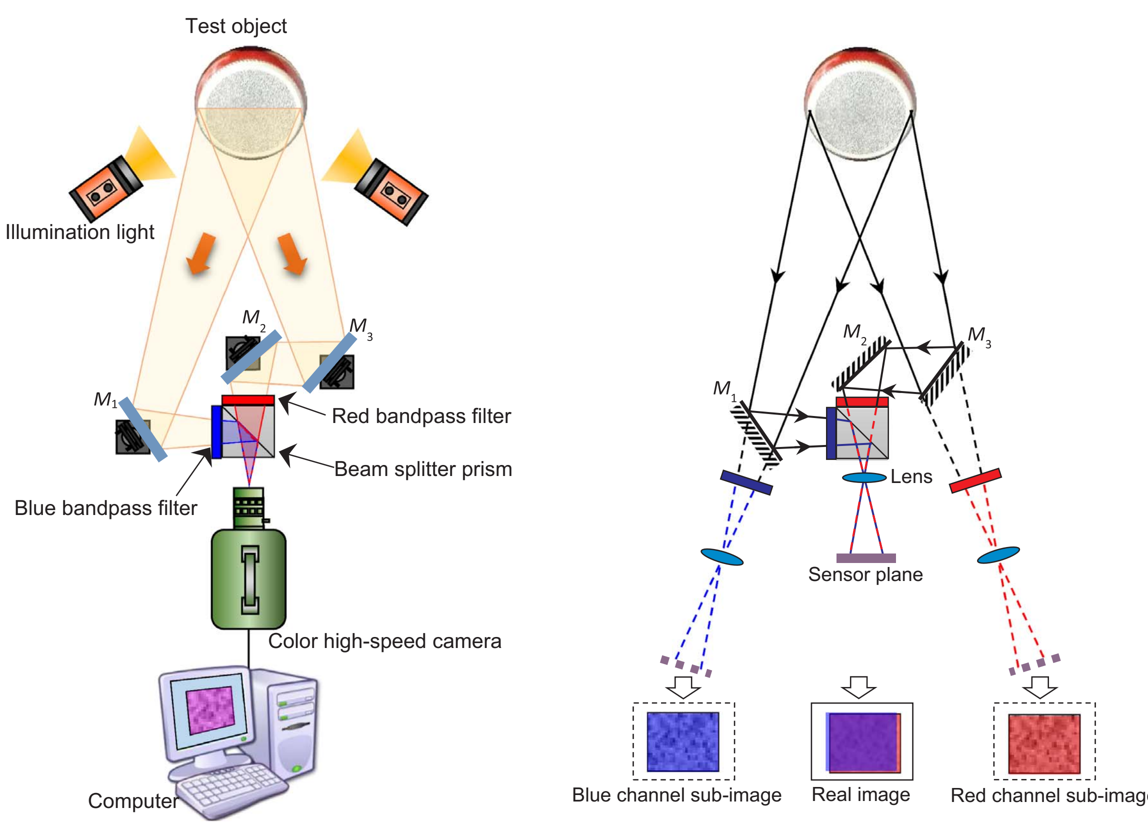

Fig. 1. Optical arrangement of the established single-camera high-speed stereo-DIC system.