Research Article

Vibration Measurement of a Metal Sheet Using Single-Camera Digital Image Correlation with Projection Components

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Digital image correlation has emerged as a popular method for the dynamic performance measurement of metallic and polymer sheets, owing to the benefits of being a noncontact, full-field, and high-precision method. Two or more high-speed cameras are required for full-field vibration measurements with three-dimensional digital image correlation, which is generally costly. Perpendicular view to the specimen surface is conventional in two-dimensional digital image correlation, and the out-of-plane displacement is regarded as a part of systematic errors. In this study, a single view method was implemented with no complex optical settings. The full-field vibration displacement of the metal sheet was measured with projection components, and the first four orders of displacement modes were identified. Finite element analysis and traditional experimental modal analysis were then implemented to validate the effectiveness and accuracy of the proposed approach. The results show that the dynamic parameters, including the natural frequencies and mode shapes, were well consistent. Meanwhile, there is a significant difference in the length of mode shape vectors. The number of measurement points in the proposed method is 2016, which is far more than the number of measurement points in the traditional experimental modal analysis. This would be convenient and beneficial for damage identification towards thin-wall parts including turbine blade with the continuum hypothesis of mode shapes and a single-camera DIC system. It is worth noting that this is effective with conditions of small deformation vibration and no rigid-body rotation.

1. Introduction

In the past decade, the digital image correlation (DIC) method was widely studied and employed for deformation, shape, and motion measurements in various applications [1–4]. The field of mechanical performance testing of new materials and structures is revolutionary, such as additive manufacturing (AM) alloys [5], shape memory alloys (SMA) [6], and carbon fibre reinforced plastics (CFRP) [7]. In addition, it is also a new path to the crack near-field measurement [8, 9] and model updating [10]. With the development of high-speed camera performance, such as achieving maximum frame rates at full resolution, an increasing number of structural dynamic characteristics can be measured through the high-speed digital image correlation (HS-DIC) method [11, 12]. The dynamic performance measurement of metallic and polymer sheets is increased by the benefits of being a noncontact, full-field, and high-precision method [13–15]. It also benefits from the inverse-compositional Gauss–Newton (IC-GN) algorithm and parallel computing which greatly increases the computational efficiency [16–18]. However, the cost of a high-speed camera is usually in excess of $10 000, and this measurement often requires two or more cameras to capture the full-field vibration measurement through the stereo-vision method. Such a high price is close to the laser Doppler vibrometer (LDV) system. The DIC and LDV methods both have their own strengths in full-field vibration measurement [19, 20]. The essential difference between the two methods is that DIC adopts the time-frozen method and records a frame containing full-field displacement information for each sample, while LDV is generally limited to the velocity of a single point in each sample [21].
To overcome this significant drawback of HS-DIC, a series of investigations aimed at single-camera stereo-DIC systems [22–26] have been published, while the time synchronization errors caused by triggers between different cameras are eliminated, especially high-speed rotating parts measurement of the HS-DIC are potential and valuable [27]. Single-camera stereo-DIC techniques have gained increasing attention owing to their advantages of cost effectiveness, compactness, and avoidance of additional camera synchronization.

Two types of single-camera stereo-DIC systems have been proposed in recent studies. The first one adopts a biprism and a set of planar mirrors to split the single view into two different views. The two views are captured in the same CCD/CMOS sensor, which is generally divided equally by the centerline. Owing to hardware constraints, the maximum resolution of most high-speed cameras ranges from 1 to 4 megapixels, such as 1280 px×800 px. This is an extremely poor resolution of strain field measurement based on the DIC method when it is divided into two halves, usually 800 px×640 px or even less. Compared with the megapixel resolutions of low-speed cameras, the number of full-field grid in ten megapixel images is 10 times larger than above. For example, Genovese et al. [23] presented a single-camera stereo-DIC system that uses a biprism in front of the camera objective to split a single sensor into two views. Pankow et al. [24] devised a single-camera stereo-DIC system to record images at high speeds using a series of mirrors. Yu and Pan [25] proposed a single-camera high-speed stereo-DIC system using a four-mirror adapter for full-field 3D vibration measurement. One common element across these methodologies was that all these methods were confronted with low-resolution and stable accessory platforms.

The second type of single-camera stereo-DIC system adopts different optical bandpass filters to gather the two different views into the same CCD/CMOS color sensor. This method is questionable when improving the spatial resolution of the high-speed camera, considering that a monochrome camera is replaced by a color camera. This is primarily because there are many camera sensor capability penalties that should be considered in color image acquisition, such as sensor pixel size, sensitivity, and dark current, to balance the spatial resolution and image noise. For example, Yu and Pan [26] designed a single-camera stereo imaging apparatus, and the specimen surface was recorded using a high-speed color CMOS camera, with the images consisting of blue and red channels, which were from two different optical paths. A specialized camera, called a 3CCD color camera, was also trialled in a single-camera stereo-vision system. Hijazi et al. [28] demonstrated the feasibility of using a low-cost 3CCD color camera and recorded six frame sequences at frame rates up to 20 kHz, proving that it was suitable for application in quantitative and transient full-field measurements, such as DIC and particle image velocimetry (PIV). Yu and Pan [29] adopted a single 3CCD color camera for full-field shape, motion, and deformation measurements, thus avoiding sacrificing the spatial resolution of the camera sensor, with the aid of a specially designed color separation device using a beam splitter and two optical bandpass filters.

The two types of single-camera stereo-DIC system mentioned above are not limited to static and steady-state vibration measurement but also include transient response measurement as long as the frame rate and image quality are sufficient. Moreover, a new single-camera method for steady-state vibration measurement was proposed newly. Gorjup et al. [30] utilized a moving high-speed camera, extending the image-based vibration measurement method. Spatial small harmonic motion can be identified in the frequency domain. The properties of the stationary vibration response of linear, time-invariant mechanical structures are leveraged to produce full-field 3D operating deflection shape measurements using only a single monochrome high-speed camera. The disadvantage is that three or more different views are required, which signifies that at least three images are processed. In addition, multiple perspectives must have the same field of view (FOV), which is a limitation for specimen shapes. Earlier, Quan et al. [31] attempted at using the traditional 2D-DIC method and local displacement gradient feature in the image coordinate system for 3D displacement measurement. The robustness is at the risk of the filtering size and signal-noise ratio, especially for a small angle between the local normal vector of specimen surface and optical axis. Essentially, the core issue is also how to separate the component of out-plane displacement from the image coordinate system under a series of assumptions such as a linear approximation of deformation mapping with first-order shape function.

Although quite a few single-camera DIC methods have been published, various contributions devoted to metal sheet or similar composite structure vibration analysis have been proposed by several teams based on traditional 3D-DIC with two high-speed cameras. Huhady and Hagara [14] realized a huge efficiency improvement using the enhanced frequency function (EFRF) instead of FRF in modal parameter estimation procedure, with hundreds or thousands of output degrees of freedom in full-field modal analysis being necessary. Chang et al. [32] followed the adaptive geometric moment descriptor (AGMD) and combined it with K-SVD and Gram–Schmidt orthonormalization (GSO) to achieve data compression of displacement maps. Passieux et al. [33] developed a new regularized DIC method for time-dependent measurements to improve the space field uncertainties and achieve a trade-off between the frame rate and spatial resolution. Bharadwaj et al. [15, 34] migrated the strain expansion-reduction approach (SERA) from the traditional finite element analysis (FEA) to experimental mechanics. The full-field strain mode shapes from the FEA were instead obtained from the DIC results. Therefore, a metal sheet vibration measurement was also implemented in the current work.

In this study, the cumbersome settings for single-camera stereo-DIC systems, such as biprisms, mirror adapters, or optical bandpass filters, were removed completely. At the same time, it breaks the traditional methodology in 2D-DIC perpendicular to the specimen surface. Furthermore, using
projection components, the full-field vibration displacement of the metal sheet was measured with a single monochrome high-speed camera, which is subject to the classical pin-hole model and projection model. The first four order displacement mode shapes were identified and analyzed. To validate the effectiveness and accuracy of the proposed method, FEA simulations and traditional experimental modal analysis (EMA) were implemented.

2. Experimental Setup and Measuring Principles

Figure 1 schematically shows the three types of single-camera DIC experimental setups for full-field vibration measurements. A four-mirror adaptor with a monochrome camera scheme in Figure 1(a) and a set of optical bandpass filters with color camera scheme in Figure 1(b) were proposed in [24–26], which required a stable environment to hold these optical components, such as an air-floating platform in the laboratory. The scheme proposed in this study was specifically designed to have no complex optical arrangement or projection component and is shown in Figure 1(c). Although the vibration deformation is strictly a 3D curved surface, the principal vibrating directions of arbitrary point on the surface were approximately the same due to normal vectors, almost parallel with regard to the metal sheet or other small-curvature thin-wall parts. The tilt angle, $\theta$, was between the optical axis of the camera and the normal direction of the metal sheet.

The main objectives were as follows: (1) converting the projection component from the in-plane displacement to the vibration direction and (2) converting the pixel unit to an actual physical unit, such as a millimeter, according to the different spatial resolutions at different horizontal heights.

As shown in Figure 1(c), the DIC experimental setup primarily consisted of four parts: (I) a bench vice for fixed support; (II) a Phantom v2511 high-speed camera with a Nikon lens with a focal length of 85 mm; (III) a high-intensity LED light, with a power supply up to 250 W, which gave consideration both to enough luminance in low exposure time and sufficient depth-of-view in small aperture; and (IV) a laser displacement sensor (MTI Corporation, LTS-50-10) which was used to validate the single-point displacement and EMA. The specimen used was a rectangular stainless-steel sheet with dimensions of $138 \times 80 \text{mm}$ and thickness of 0.5 mm. The depth of the clamped part between the jaws was 18 mm, which gave a vibration measurement region of $120 \times 80 \text{mm}$, as shown in Figure 2(a). The weight of the specimen was 43.5 g after covering a layer of water transfer speckles on one side. Meanwhile, the weight of the bench vice was $\sim 15 \text{kg}$ to achieve a reliable fixed boundary. In Figure 2(b), a real image from the HS camera shows the effect of tilt angle, where there was little width at the tip and narrowness at the root. Owing to the tilt angle, $\theta$, the different horizontal heights have different object distances to the camera, corresponding to different spatial resolutions, with two different spatial resolutions of height approximately given by $\delta_{\text{tip}}$ and $\delta_{\text{root}}$ in (1). It is worth noting that the middle position is described in the physical coordinates rather than being described in the image coordinates. Thus, the middle position was not in the center of the image but slightly closer to the root. The enlarged four corners in Figure 2(c) showed a satisfactory imaging quality within a certain range of depth of field.
(DOF) and illumination uniformity, which benefited largely from the sufficient light intensity and small aperture. Meanwhile, a speckle is framed in a 4 px × 4 px box in the enlarged center part, illustrating that the water transfer speckle size was suitable for this experimental setup (recommended in 3 px ∼ 5 px).

\[
\begin{align*}
\delta_{\text{tip}} &= \frac{w_{\text{tip}}}{W} \approx 6.7750 \text{pixel/mm} \\
\delta_{\text{root}} &= \frac{w_{\text{root}}}{W} \approx 6.4500 \text{pixel/mm}
\end{align*}
\]

In addition, the image resolution was 800 px × 640 px at 2000 frames per second (FPS), with an exposure time of 20 μs. There were 8101 images recorded for each excitation at around 4.05 seconds. It should be noted that the conventional local-DIC tracking algorithm was employed, including an initial value estimation and zero-mean normalized sum of the squared difference (ZNSSD) criteria optimization with a first-order shape function. There were 9801 points within the trapezium region of interest (ROI). A grid spacing of ~2 mm and a subset size of 31 px × 31 px were set for data processing.

The bold arrows in Figure 3(a) represent the metal sheets, with the capital letter \( H \) representing the object size in millimeters and the small letter \( h \) representing the pixel size in the image. Three different spatial resolutions represent the three different object distance planes along the optical axis. \( \delta_{\text{middle}} \) was defined in the precise middle of \( \delta_{\text{tip}} \) and \( \delta_{\text{root}} \), as shown in (2). According to geometric similarity, the tilt angle, \( \theta \), was derived using (3) and (4), in this case. Combined with the projection relationship in Figure 3(b), the first step was to convert the in-plane displacement to the vibration direction. The vibration response was then derived.

\( \delta_{\text{root}} \) was defined in the precise middle of \( \delta_{\text{tip}} \) and \( \delta_{\text{root}} \), as shown in (2). According to geometric similarity, the tilt angle, \( \theta \), was derived using (3) and (4), in this case. Combined with the projection relationship in Figure 3(b), the first step was to convert the in-plane displacement to the vibration direction. The vibration response was then derived.
Figure 4: Laser and DIC measurement results of a single-point response of impulse excitation: (a) time domain; (b) frequency domain.

from the DIC results in (5), where \( \delta_y \) denotes the local spatial resolution, \( d_1 \) represents the DIC tracking results in the \( y \)-direction in pixels, and \( d_2 \) represents the vibration response associated with \( d_1 \). The vibration response, \( D \), in millimeters was defined from \( d_2 \) and \( \delta_y \) in (5).

\[
\delta_{\text{middle}} = \frac{\left( \delta_{\text{tip}} + \delta_{\text{root}} \right)}{2} \approx \frac{6.125 \text{ pixel}}{\text{mm}},
\]

\[
\delta_{\text{middle}} = \frac{h}{H \cdot \cos \theta},
\]

\[
\theta = \arccos \left( \frac{h}{H \cdot \delta_{\text{middle}}} \right) \approx 13.98^\circ,
\]

\[
D = \frac{d_2 \cdot \delta_y}{\delta_{\text{middle}}} = \frac{d_1}{d_1} \cdot \sin \theta.
\]

The origin of the pixel coordinates was located at the top-left corner of the image. In this case, the \( y \)-coordinate of tip line AB was around \( y_{\text{tip}} = 10 \text{ px} \), and the root line CD was around \( y_{\text{root}} = 780 \text{ px} \). The variable upper bound integral expression of the local spatial resolution can then be written as (6) under the boundaries of \( \delta_{y=10} = \delta_{\text{tip}} \) and \( \delta_{y=780} = \delta_{\text{root}} \).

\[
\delta(y) = \delta_{\text{tip}} + \left( \delta_{\text{root}} - \delta_{\text{tip}} \right) \frac{1}{H} \int_{\delta_{\text{middle}}}^{y} \frac{1}{\delta(y)} \, dy,
\]

when solved as the following equation:

\[
\delta(y) = \sqrt{ky + b}, \quad y \in [1, 800],
\]

Therefore, the metal sheet vibration displacement was mapped from the DIC tracking results using (5) and (7).

3. Results and Discussion

3.1. Measurement Results of Proposed Method. As shown in Figure 4, a single-point displacement response was compared between the laser displacement sensor and DIC results in the time and frequency domains. The position of the measuring point was near the tip corner on both sides of the metal sheet, as shown in Figure 4(a). In the time-domain diagram, the two displacement response curves were generally consistent, with a redundant low-frequency component in the DIC results of approximately 5 \( \text{Hz} \), which was considered as the shake of the camera system. The influence of this low-frequency component in the data process was ignored because it was far less than the modal frequencies, and more details about the influence of the camera rotation can be found in [35]. Through the fast Fourier transform (FFT) and logarithm operation, the displacement amplitude spectra are presented in Figure 4(b). The first four modal frequencies were picked with ranges from 29.00 \( \text{Hz} \) to 330.25 \( \text{Hz} \), and the frequency resolution is 0.25 \( \text{Hz} \).

The full-field displacement response under impulse excitation is shown in Figure 5, and several vibration modes were excited. These nine frames represent a series of deformations in 0.04 \( \text{s} \) intervals, which was little more than a period of the first-order vibration modal. Comparing \( T = 0.005 \text{s} \) and \( T = 0.040 \text{s} \), the duration from \( T = 0.005 \text{s} \) to \( T = 0.040 \text{s} \) went through a period of the first-order vibration modal approximately, which was the first bending mode. It went through approximately half a period of the second-order modal vibration, which was the first torsion mode. The modal analysis results in Section 3.2 provide more accurate mode shapes of the single edge fixed metal sheet. In Figure 5, the clamped edge was
around the line \( y = 120\text{mm} \), where the displacement response is close to zero at every moment. At the other end, the maximum amplitude of the displacement response was approximately 1mm.

3.2. Modal Analysis and Validation. In this section, the poly-reference least-squares complex frequency-domain method (p-LSCF) [36] was employed for modal parameter identification of experimental data. Compared with the traditional EMA method, the DIC results have thousands of vibration receiver points and were a challenge for the parameter identification process due to the cost function size of the reduced linear least-squares estimates, detonated by the large frequency response function matrix (FRF). In a recent study, an approximated enhanced frequency response function (EFRF) was utilized to reduce the matrix size [14], computational time, and memory usage. In the current work, 2016 output channels of DIC results were implemented for modal parameter identification. The stable chart is shown in Figure 6, and the poles of the first four vibration modes, which lie in the 33\textsuperscript{rd} model order of the polynomial basis function, were selected.

The EMA and FEA validations were implemented. In this traditional EMA, there are 25 points for the laser displacement sensor successively, and the hammering point was invariable at point 25, as shown in Figure 2(a). In the simulation FE model, it was necessary to demonstrate some material parameters, such as the density, \( \rho = 7.93 \times 10^3\text{kg/m}^3 \); Young’s modulus, \( G = 199\text{GPa} \); and Poisson’s ratio \( \nu = 0.3 \). The solid shell element dimension was \( \sim 1\text{mm} \). A total of 9801 nodes on the metal sheet were extracted in the modal analysis. The boundary condition

![Figure 5: Full-field displacement of vibration response under the impulse excitation at a series of moments from \( T = 0.005\text{s} \) to \( T = 0.045\text{s} \).](image)

![Figure 6: Stable chart of modal parameters identification using p-LSCF method. The original displacement data is from the proposed single-camera DIC results. The first four vibration modes’ poles, which lie in the 33\textsuperscript{rd} model order of the polynomial basis function, are picked.](image)
Table 1: The first four natural frequencies and damping ratios of the proposed DIC method, EMA, and FEA results.

|                | Single-camera DIC | EMA | FEA | Frequency difference between DIC and EMA (%) | Frequency difference between DIC and FEA (%) |
|----------------|-------------------|-----|-----|---------------------------------------------|---------------------------------------------|
| $f_n$ (Hz)     | $\zeta$ (%)       | $f_n$ (Hz) | $\zeta$ (%) | $f_n$ (Hz) |                                             |
| 1st mode       | 28.83             | 1.09 | 28.52 | 0.51 | 28.94 | 1.09 | 0.38 |
| 2nd mode       | 99.81             | 0.83 | 96.26 | 0.91 | 97.52 | 3.69 | 2.35 |
| 3rd mode       | 180.49            | 0.33 | 178.94 | 0.33 | 179.87 | 0.87 | 0.34 |
| 4th mode       | 331.34            | 0.33 | 327.23 | 0.04 | 328.99 | 1.26 | 0.71 |

Figure 7: The first four mode shapes of the FEA, the EMA, and the proposed DIC method.

Figure 8: MAC of the first four mode shapes: (a) MAC of DIC and EMA results; (b) MAC of DIC and FEA results.
was unilateral fixation such as a cantilever plate. The first four natural frequencies identified from the proposed DIC method, EMA, and FEA results are listed in Table 1. The first four damping ratios of the proposed DIC method and EMA are also given, with the maximum value being only 1.09% in this small damping structure. In Table 1, the maximum frequency difference between the 2\textsuperscript{nd} mode of DIC and EMA results was 3.69%. This result was slightly better than that of previous studies in [25], which were 4.36% and 10%, respectively, corresponding to the traditional accelerometer measurements and FEA results.

As shown in Figure 7, the first four mode shapes identified from the FEA, EMA, and DIC data are presented together. The blue grids represent the reference equilibrium position, and the red grids represent the mode shapes. All modal vectors were normalized in $\pm 1$. The first and third modes are bending, and the second and fourth modes are torsion. Different numbers of nodes correspond to different grid densities, and the EMA mode shapes were the sparsest among these three groups; meanwhile, the curved surfaces of the FEA and DIC mode shapes were smooth. According to the modal assurance criterion (MAC) results in Figure 8, the MAC of DIC mode shapes with FEA and that with EMA were both acceptable. Meanwhile, the MAC with FEA was slightly better than EMA, which benefits from the simple boundary conditions and structure of the metal sheet in the FE model.

4. Conclusions

With a projection component, the vibration displacement of the metal sheet was measured using a single high-speed camera, and the FEA and EMA were validated. Firstly, a single-point displacement response was compared between the laser displacement sensor data and DIC data in the time and frequency domains. Secondly, the modal analysis results, including natural frequencies, mode shapes, and MAC matrices, demonstrated consistent results among the three different methods.

In several single-camera DIC vibration measurement schemes, this method is simpler, more convenient, and more accurate for the vibration measurement of metal sheets because there is no need for other optical devices such as mirrors or prisms, and there is no use of a color camera instead of a monochrome camera. The monochrome camera has a better sensitivity and signal-to-noise ratio than those of the color camera, which is equipped with the same size of CCD/COMS sensor.

Furthermore, this is an alternative strategy to the full-field vibration measurement of small-curvature thin-wall parts and differs from the motion camera for the multiview method [30], which requires steady-state vibration and data processing in the frequency domain. In contrast, the full-field transient response in the time domain can be recorded and processed directly through this proposed method. It is worth noting that the full-field displacement response was projected from the physical coordinates to image coordinates, assuming that the displacement is a linear mapping from physical coordinates to image coordinates. In other words, it is based on the condition that the vibration amplitude is far less than the structure size in the FOV. For most nonflexible structures, this requirement is similar to that of a natural match.

Overall, regardless of the splitting optical path or motion camera for multiple views, the scheme was designed for three-dimensional reconstruction and following traditional stereo vision with a single camera. However, when it comes to small vibration measurements of small-curvature thin-wall parts, the proposed approach is a good choice. The full-field vibration vectors could be determined through the simple affine transformation or FE model, which is expected to be applied to damage detection with mode shape continuity and more dynamic performance measurements.

Data Availability

All data, models, and codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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