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Modal shapes measurements of a rotating disc using stroboscopic 3D digital image correlation and down-sampling strategy

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Abstract

Rotating machinery plays an essential role in aerospace, energy, automotive, and other industries. A resonance phenomenon will occur if the rotational speed of the structure is close to its critical speed. Experimental analysis of the modal shapes of a rotating component at critical speeds can improve its design and performance in applications. Full-field deformation measurements of a rotating structure can be realized by three-dimension digital image correlation(3D-DIC) based on high-speed cameras. However, high-speed cameras are too expensive to apply widely. This study presents a method using 3D-DIC and a down-sampling strategy, which only uses low-cost normal-speed cameras. In order to ensure that two low-speed cameras can synchronously capture images clearly, a synchronous stroboscopic device is used. A measurement experiment was executed on a rotating disc at a critical speed to verify the availability of the method.

Measurement Principles

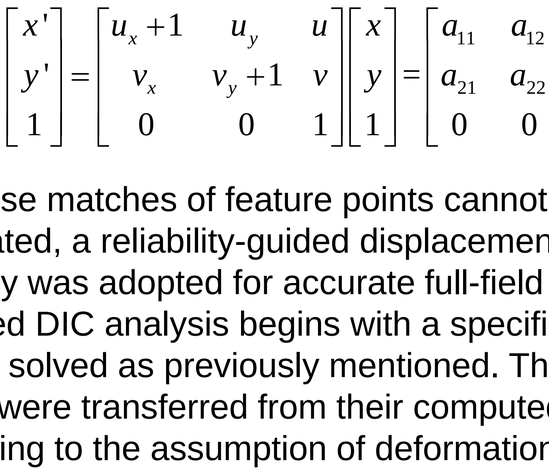
- The scale-invariant feature transform (SIFT) feature and random sampling consensus (RANSAC) algorithm were combined to obtain accurate initial value estimation in DIC. Three or more matched feature points were used to fit the affine transform, which was found equivalent to the first-order shape function.

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} u_x+1 & u_y & u \\ v_x & v_y+1 & v \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

- The false matches of feature points cannot be completely eliminated, a reliability-guided displacement tracking (RGDT) strategy was adopted for accurate full-field initial guess estimation. Full-filed DIC analysis begins with a specified seed point, which can be solved as previously mentioned. The initial guesses of rest points were transferred from their computed neighboring points according to the assumption of deformation continuity.

$$\begin{cases} u_i^0 = u_s + u_{x\_s} \times (x_i - x_s) + u_{y\_s} \times (y_i - y_s) \\ u_{xi}^0 = u_{x\_s} \\ u_{yi}^0 = u_{y\_s} \\ v_i^0 = v_s + v_{x\_s} \times (x_i - x_s) + v_{y\_s} \times (y_i - y_s) \\ v_{xi}^0 = v_{x\_s} \\ v_{yi}^0 = v_{y\_s} \end{cases}$$

- To avoid error accumulation, the strategy for correlations in 3D-DIC was used.



- Down-sampling strategy was adopted to overcome the Nyquist rate limitation. The down-sampled signal was retrieved, and spectral leakage phenomena were avoided.

$$f_s = \frac{f_v(n_s/n)}{k(n_s/n)+1}$$

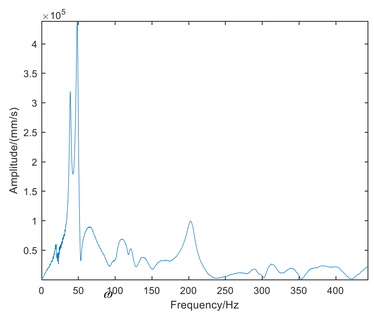
- The motion of rotating structures was composed of a rigid body motion and responses corresponding to vibration. To separate these two motion components, a method using singular value decomposition and least-squares estimation to calculate best-fitting rigid transformations was adopted.

$$\sum_{i=1}^{n} w_i \left\| (Rp_i + t - q_i) \right\|^2$$

- Due to the high rotational speed of the disc, a short shutter period of 1 μs was used to capture clear images using a synchronous stroboscopic device.

Results

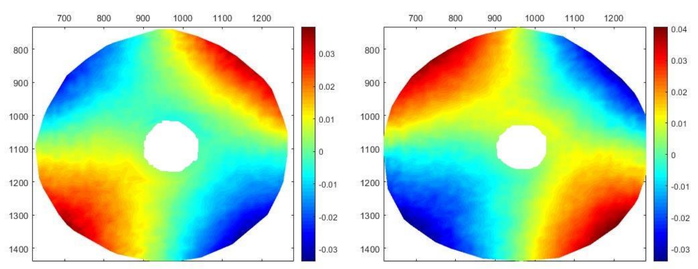
- The frequency spectrum measured by using LDV



- The result of frequency spectrum analysis(The frequency ω of maximum excitation was obtained by analysis)

rotating frequency/Hz	ω /Hz
38	38.00000025
48	48.000000375

- The out-of-plane displacement of the rotating disc at different critical speeds: (a) 38 rps and (b) 48 rps



Conclusion

In this paper, a method had been proposed for vibration measurements of rotating structures. It employed a pair of low-speed cameras and a synchronous stroboscopic device. 3D-DIC was used to measure full-field displacement. A down-sampling strategy was used to retrieve high-frequency signals. A synchronous stroboscopic device was used to minimize image blur. The availability of the proposed method had been verified by a vibration measurement experiment for a rotating disc. The experimental result showed that the out-of-plane deformation of a rotating disc at different critical speeds corresponds to the various orders of modal shape. Compared with the non-resonance state, the out-of-plane deformation of the rotating disc was significant. The result showed that the proposed method was a low-cost and non-contact experimental tool to study the dynamic behavior of a rotating component. The measured frequency must be determined precisely in the proposed method. Using LDV to determine the measured frequency in real-time can be considered for a future investigation.