Measurement 129 (2018) 436–444

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Correction of rigid body motion in deformation measurement of rotating objects

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ARTICLE INFO

Keywords:
Digital image correlation
Helicopter blade deformation
Image processing
Point cloud processing

ABSTRACT

When using image-based measurement solutions for monitoring the displacement of rotating objects, it is necessary to trigger the image acquisition system at precise positions. Triggering errors lead to artificial rigid motions in the output that are hard to remove independently. Thus, a methodology was developed to enable the removal of these errors while maintaining the true rotations, such as those relating to the angle of attack.

The proposed methodology involves detecting an object's axis and centre of rotation and then using that knowledge to correct acquired deformation data. Additionally, it also enables the representation of displacements in a more representative coordinate system, i.e., one that includes the rotation axis.

While common solutions for this problem use either manually positioned references or track a single-point's rotation, the proposed methodology is based on a least-squares approach. This results in a more accurate measurement of the rotation axis and, thus, improves the quality of the results.

The methodology was experimentally validated and it was shown that its implementation is accurate, with errors below 3%. Additionally, it was applied to an actual experimental situation and the results were compared to the uncorrected data, while highlighting the most relevant improvements.

1. Introduction

Rotating structures are commonly used for a wide range of applications, which makes their motion study important for the improvement of current solutions [1], particularly in aeronautics where most rotating objects are long and slender, exhibiting considerable deformation [2]. There are several methods to study the deformation of such objects, either with or without contact, for example using strain gauges or digital image correlation [3,4]. Image-based methods have a number of advantages over traditional methods, such as being non-contact or able to acquire full displacement or deformation fields, as opposed to point-to-point techniques [5]. As such, their use does not influence the movement/deformation of the object under study, which is important in many applications [3,6].

In recent years, image methods have been used to perform measurements in rotating objects, ranging from shafts [7] to propellers [6,8] and wind turbines [9]. Many of these works, such as [6,3,10–13,9,14,15,8,16,17], involve the acquisition of shape and displacements using 3D digital image correlation.

The alignment of the world coordinates with the rotation axis is crucial for displacement measurements [13,18,17], in that if the coordinate systems are misaligned, the comparatively large deformations along the rotation axis also contribute towards measurements along other axes. As such, this problem is often tackled by defining the rotation axis [18] and creating a new coordinate system, intrinsic to the motion. Sicard and Sirohi approached this by carefully aligning a calibration plate with the rotor hub plane and defining the coordinate system from this plate [13]. On the other hand, Winstroth et al., proposed a method where one data point from the tip of the rotor is extracted for an entire rotation, which would then be used to define a 3D circle using the least-squares method, defining the centre of rotation [18]. Other works involving rotating objects often do not approach this problem because the target of their research can be obtained even with misaligned axis. For example, Rizo-Patron and Sirohi were able to perform modal analysis [15,8], and obtain the natural frequencies and mode shapes, without considering misalignments, as it had no effect on these results.

Another important factor when performing measurements in rotating objects is that the camera should be precisely synchronized with the rotation to record the target object always in the same position [6].

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https://doi.org/10.1016/j.measurement.2018.07.049
Received 11 May 2018; Received in revised form 17 July 2018; Accepted 18 July 2018
Available online 21 July 2018
0263-2241/

However, in [16,17], it was noted that when using a static reference, its positioning is also important, as misalignments between the acquired images in stationary and the rotating situations will cause rigid-body rotations that may hide the sought-after deformations. As such, they should be avoided or removed prior to the analysis, because they only represent a different angular position and not an actual displacement.

Commercial Digital Image Correlation (DIC) software usually feature rigid body motion removal features that can remove rotations [19,20] in order to find only the deformation components of displacement [19]. For example, using VIC-3D from Correlated Solutions, there are three rigid body motion removal approaches [19]: average transformation, keeping three fixed points or just one fixed point. While the latter will not affect rotations, maintaining the original values, with the other two all displacements and rotations will be relative to either the average transformation or the three selected points. This means that to remove rotation, it is necessary to do it along all axes when using that software.

Winstroth and Seume suggest, as a final remark in [18], that one way to remove these rotations could be to realign the deformed point clouds with the reference one by minimizing the distance between them close to the blade hub. Additionally, this could also be approached using a relative technique, where the reference image is also acquired during rotation, as suggested by Stasicki and Boden [6] but with a different goal, which was that of reducing motion blur effects.

The proposed methodology is aimed at tackling simultaneously the aforementioned two problems, by defining the rotation axis using two reference situations in different angular positions and using this knowledge to align every dynamically loaded situations to one of these references, where a projection of the blade perpendicular to the rotation axis is the matching target. This enables the removal of rigid rotations that do not impact the system's function while maintaining the others, of which the attack angle is the most important example. Afterwards, that same information is used to represent the results in the new coordinate system.

In this article, a novel methodology is proposed. Then, two implemented test procedures are described. The first one deals with synthetic data and attempts to recover the parameters that were used to generate it. The other is an experimental validation procedure, where known displacements were imposed and the proposed methodology was used in order to accurately measure them. Finally, an example application is presented and the results obtained from the proposed methodology are compared with the uncorrected ones and a critical discussion is presented.

2. Proposed methodology

A novel methodology was developed to detect an object's axis and centre of rotation and use that information to correct acquired deformation data from a rotating object.

For this, an experimental setup that is similar to the one used in [17] and shown schematically in Fig. 1 was considered. It is used to measure the displacements of rotating objects, such as helicopter blades and requires that the region of interest is painted with a random speckle pattern, as the blade in the right side of the schematic.

In order to measure deformation using 3D Digital Image Correlation (DIC), it is necessary to, first, calibrate the stereo camera system using images of a known pattern and, then, acquire a pair of stereo images to define the reference situation [21]. Afterwards, while target is rotating the blades will periodically interrupt a laser beam, which generates a signal on the photodetector's output. This is then processed by the controller to trigger the high-speed cameras and simultaneously acquire stereo images of the rotating object in a particular position in space. The displacements are then obtained by comparing the reference and deformed situations [21].

The proposed methodology aims at: removing any rigid rotations that are created by misalignments between the reference and deformed

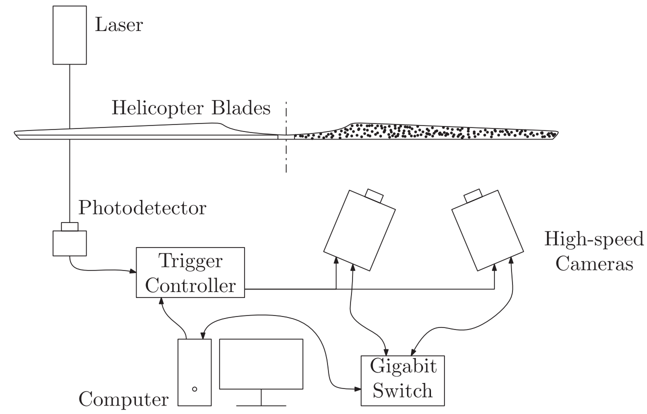

Fig. 1. Schematic of the experimental setup.

situations; and aligning the world coordinates with the rotation axis. Its main steps include:

- Acquisition of reference images for calibration of the rotation axis, in two different angular positions;
- Acquisition of images under dynamic loading conditions;
- Image processing using Digital Image Correlation [21,22], that includes the removal of *outliers* that are created in regions with poor or no speckle pattern or with other correlation issues, such as motion blurred or out-of-focus regions;
- Calculation of the rotation axis from the reference images' data;
- Projection of the data from the situations with loading in a plane normal to the rotation axis;
- Calculation of the best-fit rotation angles between these situations and a reference one;
- Correct the point clouds using the calculated rotations;
- Calculate displacements and other interest parameters.

These steps are shown schematically in Fig. 2.

The images are initially acquired and then processed with the DIC software package VIC-3D 2012 from U.S.A.'s Correlated Solutions. The resulting point clouds are exported and corrected according to the following workflow.

2.1. Calculation of the centre and axis of rotation

The first step of the methodology is to calculate the best-fit rotation axis, using the Least-Squares method developed by Spoor and Veldpaus [23,24] and taking into account Rose and Richards' suggestions [25].

Two point clouds at different angular positions of the object are used. In order to reduce errors, a large angle between them is advantageous and the reference images should have only undergone rotation along the target axis. Defining the points in the first point cloud as a_i and the ones in the second point cloud as p_i, it is possible to define one matrix for each point cloud:

$$[a] = [[a_1] \ \dots \ [a_n]], \ [p] = [[p_1] \ \dots \ [p_n]] \tag{1}$$

The centroids of both sets, $\bar{a}$ and $\bar{p}$, can be calculated simply as an average of each coordinate.

An auxiliary matrix, M, can then be calculated as:

$$M = \frac{1}{n}[a]\cdot[p]^T - \bar{a}\cdot\bar{p}^T \tag{2}$$

Matrix M can be used to calculate a symmetric matrix of Lagrangian multipliers as $S^2 = M^T\cdot M$ [23]. From the definition of eigenvalues and eigenvectors, it is seen that $M^TM = VD^2V^T$, where the eigenvectors, V_i, are the columns of matrix V and the eigenvalues, d_i, are the positive square roots of the diagonal of D^2: