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Real-time three-dimensional vibration monitoring of rotating shafts using constant-density sinusoidal fringe pattern as tri-axial sensor

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ABSTRACT

The radial and axial vibration signals of a rotating machine are crucial information to understand the machine operation and to diagnose potential faults. Instead of using three single sensors to measure the horizontal, vertical and axial displacements of rotating shafts, a novel non-projection vision-based system was proposed to realize simultaneous measurement of the radial and axial displacements with high accuracy and good reliability using an tailored artificial constant density sinusoidal fringe pattern (CDSFP), which was pasted around the shaft surface and worked as a tri-axial (i.e. the horizontal, vertical and axial) displacement sensor. The measurement principle and setup of the proposed measurement system were well established. The horizontal displacement could be correctly obtained from the fringe period density changes of the CDSFP image sequence recorded by a high-speed camera. Simultaneously, the vertical displacement could be acquired by tracking the centerline of shaft whilst the axial displacement could be obtained by locating the peaks of the cross-correlation sequence of the fringe intensities. A sub-pixel method was employed to improve the displacement resolution of the developed system. The performance of the proposed system was demonstrated by the comparison of the experiments using eddy current sensors. It showed that the proposed method was an effective and accurate technique for real-time tri-axial vibration monitoring of rotating shaft. Experimental results verified the feasibility, effectiveness and good robustness of the proposed methodology, which demonstrated that the proposed system was capable of achieving accurate tri-axial vibration displacements of rotating shaft compared to the commercial eddy current sensor which could only measure one dimensional displacement at each measurement. Therefore, the vision-based tri-axial vibration monitoring system could be recommended for real engineering applications in condition monitoring of rotating shafts.

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1. Introduction

Radial and axial vibration signals are key information for the condition monitoring and faults diagnosis of rotating machineries, such as generator, electromotor, pump and centrifugal. Since the vibration signal provides plentiful information related to system dynamics, its measurement and analysis is useful in precision machining and early warning of faults in many industrial processes. For example, Misalignment [1,2] is one of the most commonly observed faults of the shaft in rotating machines, which may be caused by improper machine assembly, thermal distortion and asymmetry in the applied load [1]. The excess of the misalignment causes the vibration of the rotatory shaft that has harmful on the rotating machines. Hence, the measurement of shaft vibration signal is very helpful in understanding the shaft vibration characteristics and further diagnosing the rotor misalignment to avoid any failure and damage.

Normally, the faults information can be characterized by frequency spectrum, orbit of shaft center and time varying feature of the shaft vibration signals. Various methods for shaft vibration measurement have been proposed by researchers and scientists, including mechanical, electromagnetic and optical methods. Generally, these vibration measurement techniques can be classified as either contact or non-contact methods. In most cases, the shaft vibration signals of rotary machineries are not accessible or difficult to directly obtain due to restrictions of vibration method or environmental limitations. Alternatively, measuring the vibration signal from the non-rotating part, such as bearing seats or shells, is an effective way to learn the knowledge of the rotary machineries. Accelerometers are preferred in many fields, which acquire the local acceleration of a specific non-rotating point of structure. Jyoti et al. [3] made attempt to reduce the number of vibration sensors by increasing the computational effort and better discriminating features for fault diagnosis of rotating machines based on vibration signal from accelerometer. Yang et al. [4] proposed a parameterized time-frequency analysis method to extract instantaneous rotatory speed from the time-domain vibration signal collected by accelerometer. Renaudin et al. [5] used three accelerometers to measure the lateral, radial and axial vibration of an experimental gearbox. However, this method will be unreliable when the vibration transmission between the rotating and non-rotating parts is low, especially for the shaft torsional vibration. Therefore, a simple and effective technique for directly shaft vibration measurement is highly desirable. As an alternative to the accelerometers, non-contact devices, such as eddy current (EC) sensors, and laser Doppler vibrometers, etc., were employed to measure the rotating objects. Patel et al. [1] used EC sensors to investigate the coupling characteristics under misalignment condition. Rothberg et al. [6] proposed a translational and rotational vibration measurement method for rotating shafts using laser vibrometry. Halliwell [7] and Xiang et al. [8] used a laser torsional vibrometer to measure the torsional vibration of a rotating shaft system. In the EC probes based system, however, three shaft displacement probes should be used to measure the displacement in horizontal, vertical and axial directions. The electrical runout also occurs in eddy current displacement measurement when shaft surface conductivity varies.

As a reliable alternative for vibration measurement, vision-based methods have undergone rapid development in recent years with the advancements in computer vision and image sensor manufacturing techniques. The advantages of this technique include noncontact measurement, no mass introduction, and effectiveness. Most common methods in vision-based system are based on object recognition and tracking through digital image correlation [9]. A high-contrast black and white pattern [10] or a special spatial coding pattern [11] was well-designed to decorate the measuring object for its ease of recognition in these systems. Guo et al. [12] proposed a template-based system to extract the rotational angle by aligning the template image in the video sequence. Recently, the authors of the paper proposed an optical coherence vibration tomography (OCVT) [13] and quasi-OCVT [14,15] using image sensor to realize non-contact vibration measurement and damage detection of beam structures. However, these methods could only measure one-axial (or one-dimensional) vibration whose direction is along the optical axis of the camera. Instead of using three single sensors (i.e., eddy current sensors) to measure the horizontal, vertical and axial displacements of a rotating shaft, a non-projection vision-based system was proposed in the present work to simultaneously measure the radial and axial displacements using an tailored artificial constant density sinusoidal fringe pattern (CDSFP). We improved the non-projection vision-based vibration measurement theory for three-dimensional (3D) vibration monitoring of a rotating shaft by using a single one CDSFP as a tri-axial sensor. Furthermore, real-time shaft orbits could be obtained by the proposed non-projection vision-based system using a single one tri-axial sensor. These are the main novelties of our present work. The proposed method can realize 3D vibration monitoring of the shaft by the vision-based tri-axial CDSFP sensor with simple but reliable signal and image processing techniques, making it promising in engineering applications of fault detection, system condition monitoring, and parameter identification for rotary machines.

2. Measurement principle of CDSFP tri-axial vibration monitoring

The schematic layout of the proposed CDSFP tri-axial vibration monitoring system was shown in Fig. 1, which consists of two subsystems: a rotor-rig system and the proposed vision-based 3D vibration measurement system. The rotational speed of the shaft can be controlled by the speed of the motor. The vision-based rotating shaft 3D vibration measurement system was simply composed of a high-speed camera, a constant-density fringe pattern and a computer. In the proposed system, the CDSFP as a tri-axial sensor was printed by a normal printer and pasted around the surface of the shaft. Initially, the lens of the high-speed camera was focused on the surface of the shaft. The optical axis of the camera was vertical to the shaft axis and was in the center of the pasted CDSFP. Therefore, the CDSFP was imaged in the center of the image sensor. The computer