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Measurement of instantaneous rotational speed using double-sine-varying-density fringe pattern

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ABSTRACT

Fast and accurate rotational speed measurement is required both for condition monitoring and faults diagnose of rotating machineries. A vision- and fringe pattern-based rotational speed measurement system was proposed to measure the instantaneous rotational speed (IRS) with high accuracy and reliability. A special double-sine-varying-density fringe pattern (DSVD-FP) was designed and pasted around the shaft surface completely and worked as primary angular sensor. The rotational angle could be correctly obtained from the left and right fringe period densities (FPDs) of the DSVD-FP image sequence recorded by a high-speed camera. The instantaneous angular speed (IAS) between two adjacent frames could be calculated from the real-time rotational angle curves, thus, the IRS also could be obtained accurately and efficiently. Both the measurement principle and system design of the novel method have been presented. The influence factors on the sensing characteristics and measurement accuracy of the novel system, including the spectral centrobaric correction method (SCCM) on the FPD calculation, the noise sources introduce by the image sensor, the exposure time and the vibration of the shaft, were investigated through simulations and experiments. The sampling rate of the high speed camera could be up to 5000 Hz, thus, the measurement becomes very fast and the change in rotational speed was sensed within 0.2 ms. The experimental results for different IRS measurements and characterization of the response property of a servo motor demonstrated the high accuracy and fast measurement of the proposed technique, making it attractive for condition monitoring and faults diagnosis of rotating machineries.

1. Introduction

The fast, continuous and accurate measurement of the rotational speed of rotating machineries, such as turbines, generators and electromotor, is very important for condition monitoring, faults diagnosis and speed maintaining. Some issues of the condition monitoring of rotating machinery have been tackled with the instantaneous angular and rotational speed analysis. Both the angular and rotational speeds are important physical quantities in rotating system, whose fluctuation can be used as the parameter for fault diagnosis [1–4]. Hence, a simple, effective and fast technique for IRS measurement is highly desirable.

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Measurement methods of rotational speed can be generally classified into two categories: analog and digital tachometer [5]. The analog tachometers are device that transduces speed into analogous or proportional signal in some other medium [6], which is widely used in feedback loops for correctly regulating the rotational speed of the drive system. The digital tachometers are device that measures the rotational speed using shaft encoders and electronic circuits [7]. Compared with the analog method, A/D converter is not needed and with better noise immunity in the digital technique. Different kinds of encoder, such as optical, magnetic, electrostatic and hall encoder, can be used in the speed measurement according the occasions and the requirements of measurement. Various measuring method utilized different principle have been studied by many researchers. Mechanical methods have been used primitively to measure the rotation angle and speed, which requires attaching an additional structure to the rotating shaft and has narrow measurement range. Jiang et al. [8] utilized an eccentric sleeve rotating with the shaft to measure the angular speed, which is only suitable for the low speed measurement owing to the eccentric force on the system. Rivola et al. [9] used a zebra tape with dark and light strips tracked by means of an optical probe to identify the instantaneous angular speed of the motorbike engine. However, the accuracy influenced by the manufacturing errors or assembly problems. Further processing was needed for performance improvement. Tachometers based on magnetic sensors were developed for the rotational speed measurement. Arif et al. [10] used rotating magnetic field for the measurement of rotational speed and calibration of tachometers with good accuracy. Giebeler et al. [11] proposed a magnetic sensor based on the giant magnetoresistance effect to measure the angular position and rotational speed. Electrostatic tachometers were also employed by researchers. Wang et al. [12] applied an electrostatic sensor in conjunction with correlation signal processing algorithms for the real-time measurement of rotational speed. Li et al. [5] proposed double correlation techniques for the improvement of rotation speed measurement based on electrostatic sensors. The utilization of the electrostatic sensor has the advantages of non-contact, cost effective and easy maintaining. However, the measurement accuracy for the lower rotational speed is not very good for these electromagnetic methods [13]. In addition, the dust around the rotor may influence its sensing.

Recently, Urbanek et al. [14] and Lin et al. [15] proposed some different techniques to estimate the IRS from the vibration signals, which has their limitations for operation in harsh industrial environment and engineering application, especially when the vibration signals contain significant noise. Rodopoulos et al. [16] proposed a simple parametric method for estimation of the instantaneous speed of rotating machines, which had lower amounts of error in comparison to Hilbert transform and Discrete Energy Separation Algorithm (DESA). Xi et al. [17] proposed a novel method including a frequency-shift synchrosqueezing transform and Viterbi algorithm for an accurate instantaneous speed estimation of rotating machinery, which was less sensitive to noise, especially for high-frequency component. Vision-based measurement systems [18–21] for rotation angle have undergone rapid development in recent years. This kind of methods can realize non-contact measurement for dynamic rotational angle of large structure decorated by a high-contrast black and white pattern or a special spatial coding pattern. However, the full image of the pattern needs to be recorded for template tracking, in which the frame rate of the camera is limited and the data storage space is big. Moreover, this kind of method puts forwards high requirements on image-processing and motion tracking algorithms to ensure the effectiveness and robustness. The authors of the paper realized high accuracy vibration measurement by means of analyzing the recorded interferogram from a 2D-optical coherence vibration tomography (2D-OCVT) system [22,23]. Recently, a Quasi-OCVT system [24,25] for structural vibration measurement was inspired by the principle of the 2D-OCVT system, in which a designed quasi-interferogram artificial fringe pattern (QIFP) was worked as a vibration sensor. In the present work, a novel vision-based IRS measurement system is proposed, which is simply composed of a well-designed artificial double-sine-varying-density fringe pattern (DSVD-FP) as a sensor and a high speed camera as a detector. Advantages of the proposed technique (e.g., noncontact measurement, low cost, and easy usage) make it attractive for the IRS measurement in engineering applications.

2. Vision-based IRS measurement system

2.1. Measurement principle and experimental device

The vision-based IRS measurement system including a computer, a cable, a high-speed camera, a special double-sine-varying-density fringe pattern (DSVD-FP) is shown in Fig. 1. The DSVD-FP as a sensor was printed by a normal printer and pasted on the surface of the shaft completely. The high-speed camera used for capturing DSVD-FP image sequence was focusing on the shaft surface from a side. The optical axis of the camera was vertical to the axis of the shaft. The computer was used to control the high-speed camera and store the image data transmitted from the camera through a GigE cable. The IRS of the shaft can be obtained from fringe density information that extracted from each DSVD-FP image, i.e., each FPD along the shaft axis corresponds to a rotation angle. Subsequently, the IRS can be calculated from the ratio of the angle difference to time difference between two adjacent frames.

In order to demonstrate the feasibility and verify the performance of the proposed method in IRS measurement, an experimental system was set up as shown in Fig. 2. A homemade rotor system was built up and fixed on a heavy optical platform. As shown in Fig. 2(a), a shaft with a diameter of 15 mm was mounted on the bearing seats. The shaft was connected with an AC servo motor (60CB040c, SYNTRON, China) through a rigid coupling. The servo motor was controlled by a servo driver (GS0040A, SYNTRON, China) and the rotation speeds are proportional to the input voltages from a NI DAQ (USB-6003) or signal generator (Agilent 33220A) to the servo driver. A built-in encoder was used for measuring the rotating velocity of