Vibration measurement using a low-cost imaging sensor and image processing techniques

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Abstract. Vibration measurement is essential for the monitoring of rotational machineries in a variety of industries. This paper presents a novel method using a low-cost imaging sensor and image processing techniques to measure the vibration of a rotor. A series of regions of interest in the captured images is selected to extract useful information for vibration measurement. Digital image correlation is applied to evaluate the similarity level of the regions of interest between sequential images and the reference image. Vibration measurement of a rotor is achieved through the spectral analysis of the signal indicating image similarity level. Experimental assessments of the proposed method were conducted on a purpose-built test rig where a commercial eddy current sensor was used to provide reference data. Experimental results demonstrate that the vibration frequencies and their relative amplitudes from the proposed measurement system agree well with those from the reference sensor. Meanwhile, the rotor vibrates at several distinct frequencies that increase with the rotational speed and hence agrees the expected vibration characteristics.

1. Introduction
Rotational machineries are widely seen in a wide range of industries such as power, manufacturing and transportation. Vibration of an individual component in a rotating machinery poses a potential risk to process safety and affects production efficiency and maintenance requirement of the whole unit. Therefore, vibration measurement is desirable for condition monitoring, fault diagnosis and failure prognosis of rotational equipment in many industrial processes. Over the last few decades a variety of techniques based on mechanical, magnetic and electrical principles have been developed for vibration measurement [1]. The most common mechanical vibrometer is the piezoelectric accelerometer [2]. However, the applicability of such devices is limited due to the contact-type installation. Eddy current sensors are merely suitable for the direct non-contact measurement of metallic rotors while electrostatic sensors are normally utilized for dielectric rotors [3, 4]. When these two types of sensor are used to measure a rotor with other materials, appropriate markers on the rotor surface are required.

With the rapid development of imaging sensors and image processing algorithms in recent years, vision-based approaches have been becoming a promising alternative to conventional techniques for vibration measurement [5]. A most common method is based on object recognition and tracking [6, 7]. In order to achieve high measurement performance, high-resolution imaging devices are usually applied. In this case, the measurement systems have the disadvantages of low affordability and high computation...
complexity. In this paper, a low-cost imaging system is developed for vibration measurement through image similarity evaluation and frequency analysis. The proposed measurement system is advantageous over many existing techniques, including of being non-contact, cost-effective and easy to install. The measurement principle, structure design and experimental verification of the proposed system are presented in the following sections.

2. Methodology

Figure 1 depicts the basic principle of the vision-based system for vibration measurement. An imaging sensor (Basler acA800-510um at a cost of ca US$500) is used to capture the images of the side face of the rotor. In general, the intensity distribution of the acquired images depends on a variety of factors, including surface properties of the rotor (i.e. surface roughness, inherent pattern, etc.), illumination conditions and background. When a suitable region of interest (ROI) is selected from the acquired images, the non-uniformity of the rotor surface in the ROI is negligible. For certain operating and environmental conditions, the intensity distribution of the ROI depends mainly on the vibration of the rotor and thus vibration information can be extracted by analysing the intensity variation of the ROI in the sequence of captured images. Figure 2 illustrates a typical image of the rotor captured by the low-cost imaging device. The selected ROI in the image is marked by a red rectangle. A zoomed-in view of the ROI is illustrated in figure 3. In this case, the ROI has a resolution of 160×120 pixels and its intensity distribution varies with time due to the rotor vibration.

![Figure 1. Principle of the measurement system.](image1)

![Figure 2. Typical image of the rotor.](image2)

![Figure 3. Zoomed-in view of the region of interest.](image3)

In this paper, image correlation algorithm is employed to quantify the intensity change in the region of interest in an image sequence [8]. The correlation coefficient indicates the degree of similarity between the ROIs with the same size. For two image subsets X and Y with a resolution of m×n pixels, the correlation coefficient \( r \) is defined as:

\[
r = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} [X(i,j) - \overline{X}][Y(i,j) - \overline{Y}]}{\sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} [X(i,j) - \overline{X}]^2 \sum_{i=1}^{m} \sum_{j=1}^{n} [Y(i,j) - \overline{Y}]^2}}
\]

where \( X(i,j) \) and \( Y(i,j) \) are the intensity levels at the point \((i,j)\) in the image subsets \( X \) and \( Y \), respectively. \( \overline{X} \) and \( \overline{Y} \) are the mean grayscale values of the image matrices \( X \) and \( Y \), respectively. The larger the correlation coefficient, the higher the similarity between the two image subsets. In this measurement system, the average of the first 10 images is regarded as a reference image to ensure the reliability of the measurement. With a continuous comparison with the intensity distribution of the ROI in the
reference image, an image sequence is transformed to a time-domain signal, indicating the similarity level of the ROI in sequential images. Once the signal indicating the similarity level is obtained, frequency analysis of the signal is conducted to determine the main vibration modes and their relative amplitudes.

3. Experimental results and discussion

3.1. Experimental setup

Experimental tests with the vision-based measurement system were conducted on a purpose-built test rig, as shown in figure 4. The rotor is made of stainless steel with a diameter of 60 mm, connecting with an AC servo motor through a rigid coupling. The imaging device is placed perpendicularly to the axis of the rotor. A strip-shaped LED light source is employed to control the illumination conditions and ensure a consistent contrast between the rotor and background. A laptop is used to control the camera and store the images captured from the camera through a USB 3.0 cable. ROI selection, digital image correlation and frequency analysis are realized in the laptop. In this study, a commercial eddy current sensor (model HAD-STV75-77, Heng Odd Instrument Co.) mounted next to the rotor surface is used to obtain an independent reference to verify the measurement performance of the proposed system.

![Figure 4. Experimental setup of the vibration measurement system.](image)

3.2. Vibration measurement results

The performance of the vibration measurement system was validated against the eddy current sensor through comparisons between the frequency spectra from the two systems. Figure 5 shows the frequency spectra of the measurements from both sensors at the rotational speed of 600 RPM. In order to present a better comparison between the amplitude spectra, the results from the two systems are normalized with respect to their own peak magnitude. As indicated in figure 5, the two amplitude spectra are almost identical and there exist strong, well-separated spectral peaks at the fundamental and high order harmonic frequencies in both vibration measurements. In addition, the relative magnitudes of the spectral peaks in both spectra agree well with each other, although there exist slight discrepancies due to the different measuring mechanisms. In this study total harmonic distortion (THD) is used to quantify the relative magnitudes of harmonic components in the frequency spectra from the two systems. The THD value of the signal from the imaging system is -16.9 dB whilst the THD value of the signal from the eddy current sensor is -24.6 dB. The slightly higher level of THD of the similarity level signal indicates the higher powers of high order harmonic frequencies in the spectra from the imaging system. This outcome is due to the fact that the imaging system is more sensitive to the inherent surface non-uniformity of the rotor than the eddy current sensor. The results demonstrate that the proposed measurement system is capable of identifying the vibration frequencies and their relative amplitudes accurately. In addition, the agreement between the spectra from both systems verifies that the intensity variation of ROIs in acquired images is mainly attributed to the rotor vibration.

Figure 6 shows the vibration amplitude spectra at the speeds of 600 RPM and 1200 RPM. It can be seen that the fundamental vibration frequency is exactly the rotational frequency and the rotor vibrates...
at several distinct frequencies that increase linearly with the rotational speed. It is also shown that the spectral peaks become stronger at a higher speed, suggesting that the vibration displacement becomes larger. Such a spectral pattern agrees with the expected vibration characteristics, which validates the effectiveness of the proposed measurement system for vibration measurement.

![Normalized amplitude spectra of the signals from both systems. (a) Signal from the imaging system. (b) Signal from the eddy current sensor.](image1)

**Figure 5.** Normalized amplitude spectra of the signals from both systems. (a) Signal from the imaging system. (b) Signal from the eddy current sensor.

![Normalized amplitude spectra of the signals from the imaging system at different speeds. (a) 600 RPM. (b) 1200 RPM.](image2)

**Figure 6.** Normalized amplitude spectra of the signals from the imaging system at different speeds. (a) 600 RPM. (b) 1200 RPM.

4. Conclusions

In this paper, a novel measurement system using a low-cost imaging device in conjunction with image correlation and frequency analysis has been designed and implemented. The validity of the proposed measurement system has been verified with reference to a commercial eddy current sensor. The results have demonstrated that the vibration frequencies and their relative amplitudes obtained from both systems agree well with each other. In addition, experimental tests at different rotational speeds have been conducted. The experimental results have shown that the rotor vibrates at well-separated modal frequencies which increases linearly with the rotational speed. Further work will focus on the investigations into relevant factors that may affect the measurement system, including frame rate, exposure time and illumination conditions as well as field trials of the system.

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