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An approach based on wavelet packet decomposition and Hilbert–Huang transform (WPD–HHT) for spindle bearings condition monitoring

Leh-Sung Law [a], Jong Hyun Kim [a], Willey Y.H. Liew [b], Sun-Kyu Lee [a,*]

[a] School of Mechatronics, Gwangju Institute of Science and Technology, Oryong-dong, Buk-gu, Gwangju 500-712, South Korea
[b] School of Engineering and Information Technology, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia

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ABSTRACT

In order to prevent possible damages to the spindle systems, reliable monitoring techniques are required to provide valuable information on the condition of the spindle condition. A technique is proposed for monitoring spindle bearings conditions via the use of acoustic emission (AE) signals, which implements Hilbert–Huang transform (HHT) analysis to extract the crucial characteristic from the measured data to correlate spindle running condition. The HHT becomes a promising technique in extracting the properties of nonlinear and non-stationary signal. However, the original HHT has several deficiencies, which eventually lead to misinterpretation to the final results. The improved version of HHT is proposed and used to overcome the weakness of the original HHT. The simulation and experimental results are used to verify the effectiveness of the WPD–HHT and therefore Hilbert marginal spectral, compared to traditional Fourier transform. Experimental results are presented to examine and explore the effectiveness of AE for monitoring spindle bearings conditions. It is concluded that good correlation existed between the results obtained by AE data and the increase in the preload, and change in the dimensions and geometry of the spindle bearings and their housings as the temperature increases. In support of this finding, vibration and acceleration data are also used to assess the amount changes in the antistrophic stiffness and radial error motion.

1. Introduction

Shaft and bearing systems form the heart of many machines and mechanisms such as machine tool spindles, engines and turbo-machinery. The speed and the load carrying capacity of the bearings are the crucial elements in the accurate performance of the machines. Under dynamic condition, an assortment of problems related to the application of periodic shock loads, out-of-balance rotation of inertial elements and bearing induced forces create vibration to the system. These untoward motions in the case of machine tool spindles can in turn induce a host of problems, such as damage to machine elements, machined surface inaccuracies and irregularities. The main sources of the vibration that have significant influences on the performance of machine tool spindles include inherent vibration of machine elements such as bearing supports due to the variable compliance effect, manufacturing defects of the contacting parts, out-of-balance assembly, natural modes of spindle components, cyclic loading produced by disengaging and engaging of the cutting tool with the workpiece [1–4].

* Corresponding author. Tel.: +82 62 715 2388; fax: +82 62 715 2384.
E-mail address: skyee@gist.ac.kr (S.-K. Lee).

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Regardless of the degree of control in manufacture and assembly, choice of bearing support and bearing setting, small geometric inaccuracies, insufficient pre-loading of bearing and inadequate interference fitting to the shaft cause out-of-balance rotations of spindle, which in many cases contribute significantly to the vibration of the spindle [5,6]. According to relevant studies, 40–70% of errors on machine tool spindle are resulted from the thermal deformation [7–18], where the main source of heat lies in the friction between spindle and transition belt, and that between spindle and roller bearing. They also investigated the effect of the thermal deformation of bearing surroundings on the machine tool spindle system, which showed a tendency to the periodic change in spindle stiffness. Roller bearings with single or multiple arrangements are most commonly used on machine tool spindles. The rate of the heat dissipated from the outer ring through the housing components is normally faster than that dissipated from the inner ring through the spindle body and by convection. This in turn creates a temperature gradient between the inner and outer rings. Thermally induced radial expansion of the inner ring directly changes the preload setting during mounting, leading to an increase in the heat generation in the bearing [19]. When the bearing is no longer able to dissipate the heat quickly from the inner ring, this may result in an instant destruction of the bearing. Therefore, condition monitoring of the spindle bearings is important for precision manufacturing process.

This paper reports the application of an advanced signal processing method to process the acoustic emission data to produce valuable information on the condition of the spindle bearings. The vibration and acceleration data are used as a reference in comparing the effectiveness of using acoustic emission data to correlate to the preload changes caused by the heat generated in the bearing and an uneven temperature gradient in the bearing housing. The effect of the temperature growth within the bearings on the characteristic of the frequencies of the machine tool spindle are monitored and assessed. Four different radial forces were exerted on the spindle shaft using an Electromagnetic exciter (EME). The system is used to investigate the change in the anisotropic stiffness of the machine tool spindle bearings with temperature.

2. Signal processing

The research on machine condition monitoring have shown that information gathered from machine-integrated sensors provides useful insight into the real-time behavior of the machines under various operating conditions, thus enabling early identification of incipient spindle bearings faults. Vibration, acoustic emission, temperature, force and torque variations are signals commonly monitored for the purpose of evaluating the condition of the machine. However, vibration signals are directly related to a spindle's structural dynamics and working conditions and hence commonly used as effective indicator of potential machine failure [20–23].

Several studies have shown that Acoustic Emission (AE) technique is effective in monitoring spindle bearing condition [24–27]. Miettinen and Patanitty [28] denoted that the use of AE method in the monitoring of faults in an extremely slowly rotating bearing. With the AE method, the fault in the bearing could be identified with the slowest rotational speed (0.5$\sim$5 rpm). Another work undertaken by Jamaludin et al. [29] investigated the applicability of stress wave analysis for detecting early stages of bearing damage at a rotational speed of 1.12 rpm. Choudhury and Tando [30], investigated the usefulness of AE method for deflect detection in rolling element bearings. He et al. [31] investigated the AE characteristics of bearing defect and validates the relationship between various AE parameters and operational condition of rolling bearings. The proposed method was found to be very effective in extracting the actual characteristic frequency of the bearing by AE signal. Furthermore, the AE parameters were always sensitive to the running and fault conditions, which had a strong influence on strain and deformation within the bearing material. Al-Ghamd et al. [32] has shown a comparative experimental study on the use of AE and vibration analysis for bearing defect identification and estimation of defect size. This study revealed that AE can offer earlier fault detection and improve identification capabilities than vibration analysis. Furthermore, the AE technique also provided an indication of the defect size, allowing the user to monitor the rate of degradation on the bearing; unachievable with vibration analysis.

Due to the complex nature and great variety of the spindle bearings employed in spindle systems, it is generally difficult or not feasible to assess the status of a machine directly from the raw AE signals. Feature extraction and selection techniques need to be employed to identify the occurrence of new signal characteristics and patterns, which indicate the status change of the spindles being monitored. Traditional techniques in the time and frequency domains are vulnerable to noise contamination and interference from undesired signals; hence their effectiveness in accurate spindle bearings condition monitoring and assessment is limited. Commonly employed spectral analysis technique such as FFT is based on the assumption of stationary signals [33], and is inherently unsuited for non-stationary, transient signal analysis. From the past decade, wavelet transform (WT) has become one of the fast-evolving mathematical and signal processing tools [34]. The basic operation of wavelet transform involves the operations of dilation and translation, which lead to a multi-scale analysis of the signal. Hence it can extract both time and frequency features of the inspected signal effectively. Although wavelet transform is capable of analyzing nonlinear and non-stationary signal and deemed suitable for AE based spindle bearings condition monitoring, many deficiencies have been reported in the use of wavelet transform [35].

2.1. Hilbert–Huang transform

Due to the deficiencies of wavelet transform, a new type of time–frequency analysis called Hilbert–Huang transform (HHT) has been proposed for analyzing nonlinear and non-stationary signals [36,37]. The HHT is truly an adaptive time-frequency