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Research article

Detecting weak position fluctuations from encoder signal using singular spectrum analysis

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ABSTRACT

Mechanical fault or defect will cause some weak fluctuations to the position signal. Detection of such fluctuations via encoders can help determine the health condition and performance of the machine, and offer a promising alternative to the vibration-based monitoring scheme. However, besides the interested fluctuations, encoder signal also contains a large trend and some measurement noise. In applications, the trend is normally several orders larger than the concerned fluctuations in magnitude, which makes it difficult to detect the weak fluctuations without signal distortion. In addition, the fluctuations can be complicated and amplitude modulated under non-stationary working condition. To overcome this issue, singular spectrum analysis (SSA) is proposed for detecting weak position fluctuations from encoder signal in this paper. It enables complicated encode signal to be reduced into several interpretable components including a trend, a set of periodic fluctuations and noise. A numerical simulation is given to demonstrate the performance of the method, it shows that SSA outperforms empirical mode decomposition (EMD) in terms of capability and accuracy. Moreover, linear encoder signals from a CNC machine tool are analyzed to determine the magnitudes and sources of fluctuations during feed motion. The proposed method is proven to be feasible and reliable for machinery condition monitoring.

1. Introduction

Condition-based maintenance (CBM), also called 'predictive maintenance', is becoming recognized as the most efficient way to implement maintenance in a wide range of industries. In CBM, machine condition monitoring plays a key role to determine the current condition and predict remaining useful life [1]. Various techniques including vibration analysis, acoustic measurement, oil analysis, performance analysis and thermography are developed for condition monitoring [2]. Among them, vibration analysis is the most widely used and studied technique due to its high signal to noise ratio (SNR) and ease of use [3]. Vibration is normally collected from accelerometers mounted on the machine casing, however, it is not an ideal solution for many industrial applications. Firstly, accelerometer suffers from low SNR for large complex machine because of the long and complicated transfer path. This situation is frequently encountered in the monitoring of large-scale machinery like aircraft-engine [4]. Secondly, accelerometer can only reveal vibration above cut-off frequency, which make it vulnerable for low speed working condition such as the bearing diagnosis of wind turbine [5]. Last but not least, acceleration is sensitive to the working speed, which makes it difficult to give a consistent result at different speed. Therefore, how to conduct condition monitoring in the above situations is challenging.

With the development of measurement technology, encoders are now widely equipped on motors, CNC machines, robots, and other industrial equipment. To ensure control accuracy, the encoder resolution is selected at least 10 times higher than their designed machine precision. High resolution property enables these encoders to carry dynamic information regarding machine condition monitoring. Compared with vibration signal, encoder signal has several attractive advantages. First of all, encoders have a shorter transfer path than accelerometers since they are directly mounted on shafts or moving parts of machine. Thus they have a higher SNR and can be more sensitive to incipient defect [6]. Moreover, encoder as a position sensor measures the rotary angle or linear displacement. It has good low-frequency response and can be applied to any working speed, which also makes it possible to give consistent result at different working speeds. In addition, encoders are normally built-in sensors and add no additional test cost, which makes them ideal for condition monitoring [7].

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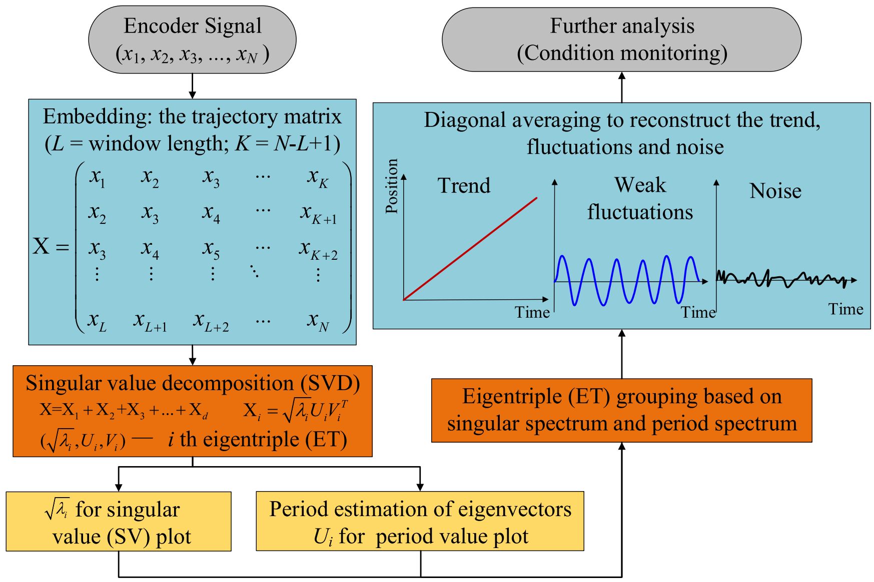

Fig. 1. Flow chart of singular spectrum analysis.

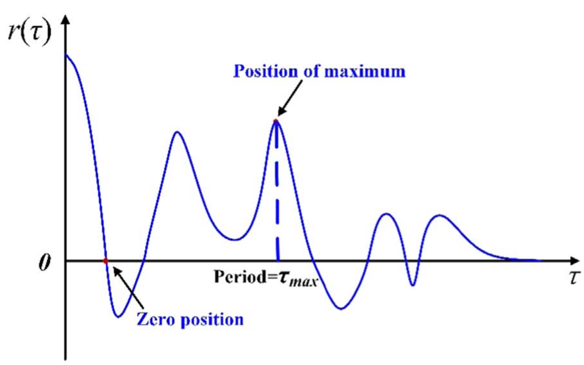

Fig. 2. Period estimation of eigenvector by autocorrelation.

Though encoder may provide a promising solution, the measured position signal needs further processing for machinery health condition. Mechanical fault, manufacturing error or electrical malfunction will cause weak fluctuations to the position signal measured by encoder. By analyzing those fluctuations, the health condition and performance of the machine can be determined and tracked [8,9]. However, the encoder signal consists of not only the interested fluctuations, but also a large trend and measurement noise. For high precision machine, the trend is several orders of magnitude larger than the fluctuations, which makes it difficult to detect the fluctuations without signal distortion.

Traditionally, researchers differentiate encoder signal to get a fluctuant representation as instantaneous angular speed (IAS) [10]. And they have applied it for dynamic transmission error analysis [6], gearbox condition monitoring [11], chatter detection [12], etc. Hoverer, IAS is sensitive to working speed like acceleration measurement, and the operation of differentiation always introduces computational error. Using both input and output position signals to calculate the difference as position fluctuations is one way to simplify the detection of the position fluctuations [7]. But the detected position fluctuations may not be accurate because the fluctuations can be caused by different response delays of the two sensors. Developing a robust signal decomposition method to detect the weak position fluctuations is essential for encoder based condition monitoring.

Classical band-pass filter [13] techniques and time-frequency methods like wavelet methods [14,15] can fulfil the task when the trend and fluctuations are well separated in distinct frequency band. However, these methods fail when their frequency bands are overlapped, which is common at low working speed. According to the review on topic of trend extraction [16], model-based approach is the most developed approach for trend extraction, but it requires assumption of the signal model. Nonparametric linear filtering methods including Henderson [17] and LOESS [18] are fast

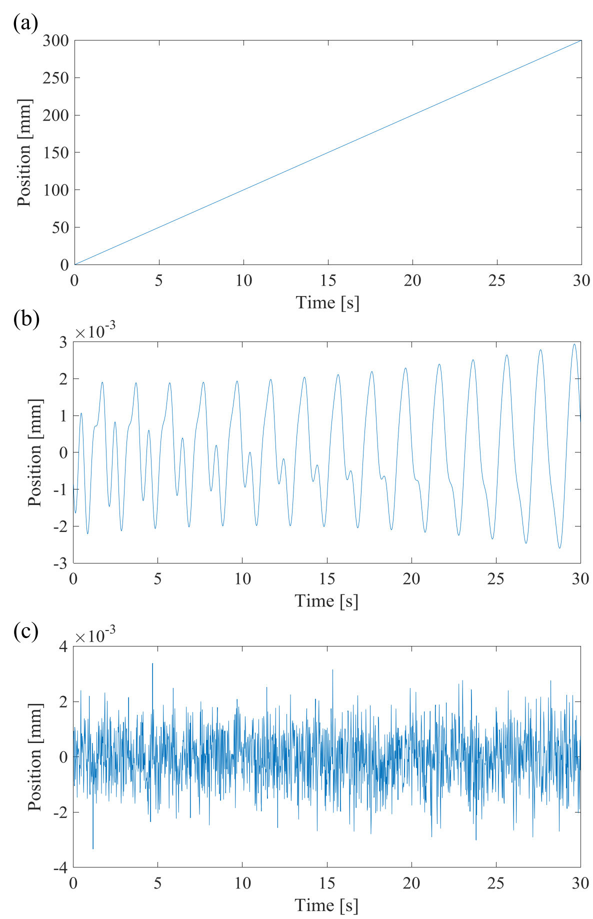

Fig. 3. Simulated signal composed by (a) trend, (b) periodic fluctuations and (c) noise.

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