Journal of Sound and Vibration 432 (2018) 484–501

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Double-dictionary signal decomposition method based on split augmented Lagrangian shrinkage algorithm and its application in gearbox hybrid faults diagnosis

Xiaoqing Yang, Kang Ding, Guolin He*, Yongzhuo Li

School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, PR China

A R T I C L E I N F O

Article history:
Received 1 August 2017
Received in revised form 13 April 2018
Accepted 28 June 2018

Handling Editor: K. Shin

Keywords:
Double-dictionary
Coupling modulation signal
SALSA
Hard threshold de-noising

A B S T R A C T

Gearbox with hybrid distributed and localized faults usually generates coupled modulation vibration signal. It is hard to decompose the coupled signal for precise diagnosis. To solve this problem, a novel signal decomposition method is proposed on the basis of double-dictionary and split augmented Lagrangian shrinkage algorithm (SALSA). The dictionary possessing high similarity to fault features consists of steady modulation sub-dictionary and impact modulation sub-dictionary. The SALSA is improved by adding a hard threshold de-noising to obtain optimal sparse coefficients of steady modulation and impact modulation components. Key parameters including Lagrange multipliers (λ_s, λ_p), penalty factor μ of SALSA and hard threshold ε are studied to determine their optimal value ranges. Kinds of simulation signals show the effectiveness of the proposed method, and experimental tests on fixed-shaft gearbox and planetary gearbox further verify the reliability. Comparative analyses with methods respectively based on matching pursuit and tunable Q-factor wavelet transform indicate that the proposed method is superior to the other two methods in calculation efficiency and anti-noise performance, especially when these two kinds of modulation components are completely coupled in some resonance bands.

1. Introduction

The gearbox, as one critical transmission component of mechanical systems, generally works under tough environment and is therefore prone to distributed faults or localized faults after longtime service. Coupled modulation vibration signals usually emerge under this condition [1]. It is very necessary for gearbox fault diagnosis to decompose steady modulation and impact modulation components from the coupled vibration signal. In recent decades, gearbox diagnosis methods based on fault feature extraction from vibration signal have attracted the majority of scholars' attention [2,3].

The Fourier transform (FT) is mainly applied to analyze the stationary vibration signal of gearbox, but is invalid to diagnose gearbox faults when the frequency components of localized faults are identical to those of distributed faults. Wavelet analysis was adopted to process the non-stationary vibration signal of rotary machinery [4–6]. The result of wavelet decomposition, however, depends on the similarity of selected mother wavelet to the waveform of faulty signal. Empirical mode decomposition [7,8] was used to adaptively obtain intrinsic mode functions (IMFs) of gearbox's vibration signal. The Hilbert-Huang transform spectra of IMFs show good results of fault diagnosis, but sometimes the IMFs may be confused.

* Corresponding author.
E-mail address: hegl@scut.edu.cn (G. He).

https://doi.org/10.1016/j.jsv.2018.06.064

Recently, many scholars have been researching sparse representation methods to diagnose gearbox faults, because of its superiorities in signal decomposition and feature extraction. Two fundamental problems of signal sparse representation are dictionary design and coefficient solution. In Ref. [9], He et al. combined correlation filtering [10] with matching pursuit [11] to diagnose rolling bearing faults. An adaptive matching pursuit algorithm [12] on the basis of impulse dictionary was proposed for rolling bearing fault diagnosis. Cui et al. [13] applied the matching pursuit to evaluate fault extents of rolling bearing based on double-dictionary and Lempel-Ziv complexity (LZC) index. In Refs. [14,15], based on the oscillatory behavior of the vibration signal, tunable Q-factor wavelet transform [16] and SALSA [17,18] were adopted to extract fault features of gearbox. Fan et al. [19] proposed a novel sparse representation method based on wavelet analysis to extract the feature components of gearbox's localized fault.

Most mentioned literature consider only the feature extraction of localized fault of gear or rolling bearing, but ignore that of distributed fault. For diagnosing hybrid faults of gearbox, it is necessary to research methods to extract steady components and impact components which are respectively caused by distributed faults and localized faults. In Ref. [20], Cui et al. designed a composite dictionary and proposed an algorithm of multi-atom matching decomposition to diagnose hybrid faults of gearbox. The genetic algorithm was applied to search for the best matching atom, and the threshold de-noising was adopted in the reconstruction algorithm. However, the dictionary lacked definite physical meaning, and the algorithm calculation was inefficient due to the matching pursuit and genetic algorithm. In Ref. [21], a segmental matching pursuit was used to sequentially extract steady components and impact components, while the accuracy of extracted impact components was highly influenced by the prior extraction of steady components.

For the above issues, this paper proposes a novel signal decomposition method based on the correlation filtering and SALSA to diagnose hybrid faults of gearbox. Here, a double-sparse-dictionary with definite physical meaning is specifically designed, and the SALSA is improved by combining the technique of hard threshold de-noising to simultaneously obtain optimal sparse coefficients of steady modulation and impact modulation components. The rest paper is structured as follows. Section 2 consists of the vibration signal model of gearbox, the method of double-dictionary design, the process of sparse coefficient solution and then the detailed procedures of the algorithm. Section 3 comes to the effectiveness validation of the proposed method by simulation signal analysis. The influences of parameters λ_s, λ_p, μ and ε on the separation results, the calculation efficiency, and comparison of the proposed method with another two methods are also discussed in Section 3. Experimental tests on fixed-shaft gearbox and planetary gearbox are further used to verify the proposed method in Section 4. Finally, conclusions are drawn in Section 5.

2. Double-dictionary signal decomposition method based on SALSA

2.1. Vibration signal model of gearbox

The steady modulation signal is originated from a distributed defect of gearbox, such as gear wear, manufacturing error or assembling error; whereas the localized fault like pitting, peeling or broken tooth, generates impact modulation components, which may be covered by the steady modulation signal or the normal gear mesh components. Therefore the vibration signals $x(t)$ of faulty gearbox usually include steady modulation components $x_s(t)$, impact modulation components $x_p(t)$ and Gaussian white noise $\eta(t)$, as described by Eq. (1).

$$x(t) = x_s(t) + x_p(t) + \eta(t) \tag{1}$$

$$x_s(t) = \sum_{m=0}^{M} B_m[1 + a_m(t)]\cos(2\pi m f_z t + \varphi_m) \tag{2}$$

where f_z is mesh frequency, B_m is amplitude and φ_m is phase. Here, $a_m(t)$ is the amplitude modulation of the mth mesh frequency, it can be expressed as

$$a_m(t) = \sum_{k=0}^{K} A_{m.k}\cos(2\pi k f_n t + \alpha_{m,k}) \tag{3}$$

where $A_{m,k}$, $\alpha_{m,k}$ are the amplitude and phase of the kth component of the mth amplitude modulation, respectively; f_n is the rotational frequency of faulty gear. When m is equals to 0 in Eq. (2), $x_s(t)$ corresponds to the rotational frequency component caused by gearbox's distributed fault [1]. The vibration response of the impact force can be described by the impulse response function (IRF) of multiple-degree-of-freedom system, which is expressed by Eq. (4).

$$h(t, \zeta, f_d) = A\exp\left[\frac{-2\pi\zeta}{\sqrt{1-\zeta^2}} f_d(t-\tau)\right]\sin[2\pi f_d(t-\tau)], \quad t \geq \tau \tag{4}$$