Mechanical Systems and Signal Processing 93 (2017) 267–280

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

# Multi-faults decoupling on turbo-expander using differential-based ensemble empirical mode decomposition

Hongguang Li [a,*], Ming Li [b,a], Cheng Li [a], Fucai Li [a], Guang Meng [a,c]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai, China
[b] Aerospace System Engineering Shanghai, Shanghai, China
[c] Shanghai Academy of Spaceflight Technology, Shanghai, China

ARTICLE INFO

*Article history:*
Received 11 July 2016
Received in revised form 4 January 2017
Accepted 10 February 2017
Available online 20 February 2017

*Keywords:*
Multi-faults decoupling
Turbo-expander
DEEMD

ABSTRACT

This paper dedicates on the multi-faults decoupling of turbo-expander rotor system using Differential-based Ensemble Empirical Mode Decomposition (DEEMD). DEEMD is an improved version of DEMD to resolve the imperfection of mode mixing. The nonlinear behaviors of the turbo-expander considering temperature gradient with crack, rub-impact and pedestal looseness faults are investigated respectively, so that the baseline for the multi-faults decoupling can be established. DEEMD is then utilized on the vibration signals of the rotor system with coupling faults acquired by numerical simulation, and the results indicate that DEEMD can successfully decouple the coupling faults, which is more efficient than EEMD. DEEMD is also applied on the vibration signal of the misalignment coupling with rub-impact fault obtained during the adjustment of the experimental system. The conclusion shows that DEEMD can decompose the practical multi-faults signal and the industrial prospect of DEEMD is verified as well.



## 1. Introduction

In 1998, Huang [1] proposed Empirical Mode Decomposition (EMD), which is a such a signal processing method that it can decompose the original signal into several Intrinsic Mode Functions (IMFs) and each IMF reflects partial characteristic of the original signal. Since the birth, EMD has been widely adopted in the fault diagnosis of rotating machineries. In the retrieved articles, Qi et al. [2] applied EMD after a cosine window processing on the vibration signal of a rotor system with rub-impact fault to solve the imperfection of end effect. Gao et al. [3] focused on the over-decomposition of EMD by combined mode function, then applied on a practical fault signal of a power generator from a thermal-electric plant. Wu and Qu [4] applied EMD on subharmonic faults of large rotating machineries and pointed out that EMD is suitable for non-stationary and nonlinear signals. Dong et al. [5] decomposed the response signal of a cracked rotor system by EMD, then applied Laplace wavelet on the IMFs for parameter identification so that the location and the depth of the crack can be identified.

However, the decoupling capability of EMD is limited to an extent. The characteristic frequency cannot be extracted efficiently by EMD without some preprocessing, for an instance, differential-based empirical mode decomposition (DEMD) [6] or stochastic resonance [7]. The characteristic ingredient can be enlarged via DEMD, and the superposing noise can be exploited using stochastic resonance. Both preprocessing methods can improve the decomposition effectiveness. In the previous paper by the authors, Li et al. [6] applied DEMD on the vibration signals of rotor system with coupling faults and

* Corresponding author.
*E-mail address:* hgli@sjtu.edu.cn (H. Li).

http://dx.doi.org/10.1016/j.ymssp.2017.02.015
0888-3270/

pointed out that DEMD can enlarge the energy in the high-frequency band where most faults have their characteristic frequency. When dealing with the rotor system with any of two combining faults of crack, rub-impact and pedestal looseness, DEMD has a better performance than EMD. However, DEMD cannot totally decompose coupling faults of crack, rub-impact, and pedestal looseness. The essential reason is the mode mixing imperfection of EMD.

For purpose of resolving the mode mixing imperfection and enhancing the decoupling consequences, Ensemble Empirical Mode Decomposition (EEMD) appears to be a better supplementation for DEMD. EEMD was proposed by Wu and Huang [8] in 2009. The algorithm of EEMD can be summarized as follows. Several white noises are superposed on the original signal, then decomposed into raw IMFs. The final IMFs are obtained by taking the average of the corresponding raw IMFs so that the influence of the white noises is eliminated. EEMD has also been widely used on fault diagnosis of rotating machineries. Lei et al. [9] applied EEMD on the rub-impact fault diagnosis of a power generator and the early rub-impact fault diagnosis of a heavy oil catalytic cracking machine set. Wu et al. [10] identified the pedestal looseness via EEMD and autoregressive modeling. Wu and Chuang [11] diagnosed the misalignment fault using hybrid EEMD and EMD. For the sake of increasing the accuracy and effectiveness of EMD, Jiang et al. [12] utilized multiwavelet packet to decompose the vibration signal into a series of narrow frequency bands, so that the weak multi-fault characteristic components can be enhanced. Jiang et al. [13] decomposed the experimental signal using EEMD, then implemented the self-zero space projection on IMFs for fault analysis. Ma et al. [14] extracted IMFs reconstructed in phase space by Hankel Matrix after EEMD, both of the simulation and experiment results implied that this method suppresses the effect of the mode mixing, improves the robustness to white noises and the weak characteristic extraction.

In this paper, the multi-faults decoupling approach Differential-based Ensemble Empirical Mode Decomposition (DEEMD) is proposed. The nonlinear behavior along with the diagnosis baseline of a turbo-expander rotor system considering temperature gradient with crack, rub-impact and pedestal looseness is investigated. Furthermore, DEEMD is adopted for the multi-faults decoupling of the vibration signals acquired numerically and experimentally. Finally, the decoupling capability of DEEMD is verified.

## 2. DEEMD

Similar with the arithmetic of DEMD [6], the detailed procedure of DEEMD can be summarized as follows,

a. Apply n-order differentiation on the original signal $x_0(t)$ to obtain the new signal $x_n(t)$;
b. Apply m-order EEMD on $x_n(t)$ and the IMFs, $c_{ni}(t)$ are obtained;
c. Integrate the IMFs, $\int c_{ni}(t)dt = b_{(n-1)i}(t) + b_{(n-1)i0}$;
d. Decompose $b_{(n-1)i}(t)$ by EMD, $b_{(n-1)i}(t) = c_{(n-1)i}(t) + r_{(n-1)i}(t)$;
e. $x_{n-1}(t) = c_{(n-1)i}(t)$, and the residue, $r_{(n-1)0} = \sum_{i=1}^{m} r_{(n-1)i}(t) + \sum_{i=1}^{m} b_{(n-1)i0}$;
f. Repeat c to e until $c_{0i}(t)$ and $r_{00}$ are obtained.

## 3. Nonlinear behavior

The vibration characteristic of the turbo-expander rotor system with faults is the very prerequisite for multi-faults decoupling. Furthermore, the nonlinear analysis should be firstly implemented because the turbo-expander rotor system is of a strong nonlinearity which will appear different oscillating features under different rotating speed. In this section, the models of crack, rub-impact and pedestal looseness are supplemented to the turbo-expander rotor system considering temperature gradient [15,16], which is abstracted in Fig. 1. The equations of the turbo-expander are presented in Eq. (1) and the value of the parameters are listed in Table 1. Herein, $X_i$, $Y_i$, $\Phi_i$, and $\Psi_i$ stands for the radial and angular displacements of the ith wheel which is illustrated in Fig. 1, and the non-dimensional form of the displacements are denoted as $x_i = X_i/C_p$, $y_i = Y_i/C_p$, $\phi_i = \Phi_i/\pi/2$, and $\psi_i = \Psi_i/\pi/2$. $C_p = c_0 - \alpha' R_0$ manifests the machining clearance under a certain temperature. $e$ stands for the eccentric length, $\zeta$ stands for damping ratio, $\tau = \omega_r time$, $\lambda = \omega_r/\omega_1$, where $\omega_r$ and $\omega_1$ is the rotating speed and first order critical speed respectively. The oil-film forces produced by the tilting pad bearings are denoted as $F_{bx2}$, $F_{by2}$, $F_{bx3}$, and $F_{by3}$ [15].

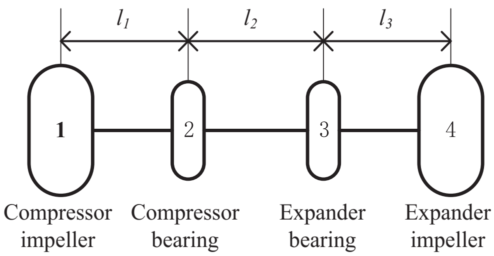


**Fig. 1.** Sketch map of the turbo-expander.