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Vibration signal analysis using parameterized time–frequency method for features extraction of varying-speed rotary machinery

Y. Yang *, X.J. Dong, Z.K. Peng, W.M. Zhang, G. Meng

Institute of Vibration Shock & Noise, Shanghai Jiao Tong University, Shanghai 200240, P.R. China

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ABSTRACT

In real application, when rotary machinery frequently involves variable-speed, unsteady load and defect, it will produce non-stationary vibration signal. Such signal can be characterized by mono- or multi-component frequency modulation (FM) and its internal instantaneous patterns are closely related to operation condition of the rotary machinery. For example, instantaneous frequency (IF) and instantaneous amplitude (IA) of a non-stationary signal are two important time–frequency features to be inspected. For vibration signal analysis of the rotary machinery, time–frequency analysis (TFA), known for analyzing the signal in the time and frequency domain simultaneously, has been accepted as a key signal processing tool. Particularly, parameterized TFA, among various TFAs, has shown great potential to investigate time–frequency features of non-stationary signals. It attracts more attention for improving time–frequency representation (TFR) with signal-dependent transform parameters. However, the parameter estimation and component separation are two problems to tackle with while using the parameterized TFA to extract time–frequency features from non-stationary vibration signal of varying-speed rotary machinery. In this paper, we propose a procedure for the parameterized TFA to analyze the non-stationary vibration signal of varying-speed rotary machinery. It basically includes four steps: initialization, estimation of transform parameter, component separation and parameterized TFA, as well as feature extraction. To demonstrate the effectiveness of the proposed method in analyzing mono- and multi-component signals, it is first used to analyze the vibration response of a laboratory rotor during a speed-up and run-down process, and then extract the instantaneous time–frequency signatures of a hydro-turbine rotor in a hydroelectric power station during a shut-down stage. In addition, the results are compared with several traditional TFAs and the proposed method outperforms others in accurate feature extraction, which is promising in applications of fault detection, system condition monitoring, parameter identification, etc.

1. Introduction

In most cases, rotary machineries, i.e., gear transmission systems, rotor, etc., are not accessible or difficult to inspect directly due to restrictions of disassembly, huge machine size or environmental limitations. Alternatively, vibration

* Corresponding author.
E-mail addresses: emma002@sjtu.edu.cn (Y. Yang), donxij@sjtu.edu.cn (X.J. Dong), z.peng@sjtu.edu.cn (Z.K. Peng), wenmingz@sjtu.edu.cn (W.M. Zhang), gmeng@sjtu.edu.cn (G. Meng).

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measurement is an effective way to learn the knowledge of the rotary machinery. Since the vibration signal provides plentiful information related to system dynamics, its analysis is the most commonly used method for condition monitoring and diagnosing of rotary machineries [1]. Considering real situation from industry, the vibration response of rotary machinery nowadays is considerable complex. The complexity typically includes the complex variations in the spectrum, non-stationary event (run-up, run-down speed, impacts, etc.), nonlinear behavior, etc. That is, the vibration signal of the rotary machinery is non-stationary. Several tasks of the signal processing in non-stationary signal analysis for rotary machines are listed as following:

(1) *Estimation of instantaneous rotatory speed*: one of the key characteristics of the vibration signal of the rotary machinery is the strong influence that the rotational speed has on the observed signal. As operation condition varies and unsteady load involves, the rotatory speed changes accordingly [2–4]. That is, the rotatory speed is a critical quantity that could reveal the non-stationary running condition and loading condition of the considered machinery [5–8]. Due to the variable-speed nature, frequency modulated (FM) vibration signals are frequently encountered. For example, in gearbox, the meshing frequency and the fault characteristic frequency of the gear are closely related to the rotatory speed. These frequencies will change when the rotatory speed of the gearbox fluctuates with the varying load conditions during the service. In rotor system, the rotary frequency and its multiplies dominate the vibration response. When the rotor experiences speed varying process, these frequencies will follow the varying rotary machinery speed. The speed can be measured by adding extra hardware, though it is costing or not easy to inspect in most cases. On the other hand, estimating the component instantaneous pattern of the mono- and multi-component vibration signal to determine the instantaneous rotatory speed is more efficient and effective.
(2) *Analysis of defect signatures*: almost all failures, i.e., rub-impact, misalignment, steam-exited vibrations, and fatigue cracks in the rotary components, can engender variations in the corresponding vibration signals. The real machines can be affected by several different types of faults simultaneously, and the vibration can be excited by several fault-related frequencies. Generally, the recurrence of the fault symptoms as the mechanical components rotate, the frequency of which, in combination with the amplitude or envelope constitute the “mechanical signature”. Capturing these mechanical signatures from the vibration response of the rotary machinery is of practical importance for both the monitoring and diagnosing purpose. The defect signature can be deduced based on the established model and monitored to detect the specific defect [9–13]. On the other hand, all possible features can be extracted from the vibration response and compared to those in perfect cases so as to construct the defect indicator [14,15]. In either case, when the rotatory speed varies, the instantaneous signatures are to be monitored and investigated, i.e., the frequency and amplitude of the high-order or non-integer multiples of the rotatory frequency and the decomposed functions of the vibration response [16].
(3) *Identification of rotary system parameters*: the parameters of the vibration system, i.e., the mass, stiffness and damping, are closely related to the nature frequency and vibration amplitude of the system. The time variation and nonlinearity of the parameters naturally result in the time-varying nature frequency and amplitude. Thus, for the vibration signal processing based system identification, it is required to establish the theoretical relationship between the system parameters to be analyzed (mode shape, mode frequency, damping, etc.) and the instantaneous features in the response signal, i.e., frequency, amplitude, frequency response function, etc. [17]. For the non-stationary response, extracting the instantaneous features from the system response is the primary step in the signal processing based system identification [18–20].

In the above cases, instantaneous frequency (IF) and instantaneous amplitude (IA) are valuable features to be extracted from the signal processing point of view, because the variations in these features correspond to fault, condition shift or nonlinear effect of the system to be identified. However, the non-constant rotatory speed always leads to the non-stationarity and multiple FM components in the measured vibration signal [21]. Hence, a persistent difficulty is how to extract these signatures properly from the non-stationary vibration response of the machine under inspection, especially when the response contains multi-component.

Overall, the vibration response in most real rotary machinery can be modeled as mono-component or multi-component FM signals [22]. Being able to analyze in the time and frequency domain simultaneously, time–frequency analysis (TFA) tool has been accepted as a key signal processing tool for the non-stationary vibration signal analysis of the rotary machinery [23,24]. In various rotary machineries, i.e., motor, rotor, gear, turbine, etc., the widely used TFAs include short-time Fourier transform (STFT) [25,26], wavelet transform (WT) [27,28], Wigner–Ville distribution (WVD) [29,30], and Hilbert–Huang transform (HHT) [31,32]. However, they are not particularly suitable to analyze the mono-component or multi-component FM signals. Specifically, the STFT and WT use the constant and scalable analysis window, respectively, which results in the signal-independent resolution and unsatisfied time–frequency representation (TFR) concentration, so that they cannot characterize the rapidly time-varying component. As a member of quadratic TFAs, the WVD, on the other hand, introduces the unwanted cross terms inevitably due to the noise or the nonlinear nature of the considered signal, which interferes the accurate TFR for the signal. The HHT combines empirical mode decomposition (EMD) and Hilbert spectral analysis which could compute the IF of intrinsic mode functions (IMF) decomposed by the EMD. Although the HHT has been widely studied, its practical applications are still blocked by several unsolved problems of the EMD, i.e., undesired low-frequency components, unexpected wide bandwidth of the first decomposed intrinsic mode function, inseparable low-energy components, etc. Unlike a typical TFA, the HHT does not involve the concept of the frequency or time resolution so it is beyond the scope of this paper.