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Sparse reconstruction of blade tip-timing signals for multi-mode blade vibration monitoring

Jun Lin [a,b], Zheng Hu [a,*], Zhong-Sheng Chen [a], Yong-Min Yang [a], Hai-Long Xu [a]

[a] *Science and Technology on Integrated Logistics Support Laboratory, National University of Defense Technology, Changsha 410073, China*
[b] *CRRC Zhuzhou Institute Co., Ltd., Zhuzhou 412001, China*

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ABSTRACT

Severe blade vibrations may reduce the useful life of the high-speed blade. Nowadays, non-contact measurement using blade tip-timing (BTT) technology is becoming promising in blade vibration monitoring. However, blade tip-timing signals are typically under-sampled. How to extract characteristic features of unknown multi-mode blade vibrations by analyzing these under-sampled signals becomes a big challenge. In this paper, a novel BTT analysis method for reconstructing unknown multi-mode blade vibration signals is proposed. The method consists of two key steps. First, a sparse representation (SR) mathematical model for sparse blade tip-timing signals is built. Second, a multi-mode blade vibration reconstruction algorithm is proposed to solve this SR problem. Experiments are carried out to validate the feasibility of the proposed method. The main advantage of this method is its ability to reconstruct unknown multi-mode blade vibration signals with high accuracy. The minimal requirements of probe number are also presented to provide guidelines for BTT system design.

1. Introduction

High-speed blades are key mechanical components in turbo machineries, such as engine compressor and turbine. They often experience severe multi-mode vibrations when exposing to extremely centrifugal forces and high-temperature operation conditions. Those vibrations will significantly reduce the fatigue life and performances of blades, which may ultimately result in catastrophic accidents. Therefore, nowadays it is urgent to carry on on-line vibration monitoring to avoid harmful stresses induced by vibrations and predict the durability and the life of blades under operating conditions.

In recent years, various blade vibration monitoring systems are developed. A traditional contact measurement method using strain gauges [1,2] attached to the blade surface is difficult to satisfy the requirements of on-line vibration monitoring. Generally, it is possible to monitor complete spectrum of blades vibration using strain gauges. However, each strain gauge only gives out analog signal related to the current blade deformation. The cost of setting up strain gauges for all blades is rather huge. An alternative blade vibration monitoring using blade tip-timing [3–6] has become promising with the advantages of non-contact and less cost. However, the sampling frequency of this method is determined by the rotating speed and the number of BTT probes. Since the maximal blade vibration frequency is always much higher than the sampling frequency, BTT signals are well under-sampled [7].

* Corresponding author.
E-mail addresses: linj@163.com (J. Lin), zhenghu@nudt.edu.cn (Z. Hu), czs_study@sina.com (Z.-S. Chen), yangyongmin@163.com (Y.-M. Yang).

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It is crucial to analyze vibration responses from these under-sampled signals. Nowadays, some studies [8–11] have been proposed to investigate blades responses from tip-timing data where each blade responds at a single frequency. However, when no prior knowledge is introduced, this condition is not guaranteed in practice. In order to extend the ability of monitoring system, Beauseroy [12] proposed a new method to analyze multicomponent blade vibration signals based on groups of optical sensors. Nevertheless, more valuable information is expected to be extracted from BTT data as much as possible. Some novel BTT analysis methods [13–16] have been developed to reconstruct spectrum-known single-model blade vibration signals. However, they are all unavailable in practice for analyzing spectrum-blind (unknown) blade vibration signals. Up to date, little work has been found on reconstructing under-sampled blade tip-timing data for unknown multi-mode blade vibration monitoring.

Sparse representation (SR) and compressed sensing (CS) [17–22] are novel theorems that have ability to reconstruct certain signals having compressibility from few under-sampled samples with accuracy. Nowadays, these techniques have been widely studied in structural dynamics and vibration analysis including output-only modal identification [23–25] and vibration based damage identification [26–28]. However, little work based on SR/CS has been proposed for extracting characteristic features of blade vibrations from BTT data. Therefore, this paper presents a new method based on SR theorem to overcome difficulties in blade tip-timing measurement. The main contribution of this method is to propose an accurate under-sampled BTT signals reconstruction algorithm when blades are vibrating at more than one frequency. In addition, the minimal requirements of probe number are also proposed to provide guidelines for BTT system design.

The left outline of this paper is summarized as follows: a SR mathematical model of the BTT measurement is built in Section 2. In Section 3, sparse representations of unknown multi-mode blade vibrations are introduced. Then a reconstruction algorithm is proposed in Section 4. In Section 5, the experimental tests are carried out to validate the feasibility of the proposed method. Finally, some major conclusions are summarized in Section 6.

2. Blade tip-timing measurement

2.1. Representation of blade tip displacements

As shown in Fig. 1, I optical-fiber probes are embedded into a stationary casing around a disk with K blades. Then the time at which the blade tips pass each probe can be measured. The angular positions of the ith probe and the kth blade are denoted as α_i and θ_k, respectively. An additional probe r is mounted in front of the shaft as a reference sensor. There is a white marker line milled on the shaft, so that the reference sensor can measure the once-per-revolution signal.

The principle of the BTT method is to measure the arrival time of a vibrating blade tip while it passes a BTT probe. The expected blade arrival time for a single non-vibrating blade at any probe are determined by the rotating speed, blade tip radius and angular position of the probe. When there are vibrations, any deviations from these expected times indicate blade vibrations with respect to the hub. These deviations are recorded by each probe as a time-series of blade tip displacements and further used to analyze blade vibration characteristics.

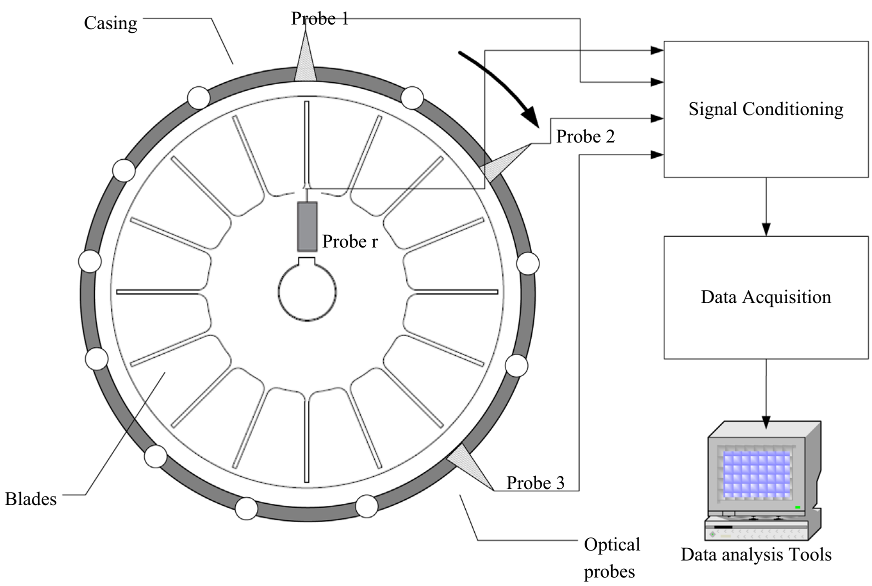

Fig. 1. Schematic of the BTT system.

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