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Blade resonance parameter identification based on tip-timing method without the once-per revolution sensor

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ABSTRACT

Blade tip-timing is the most effective method for blade vibration online measurement of turbomachinery. In this article a synchronous resonance vibration measurement method of blade based on tip-timing is presented. This method requires no once-per revolution sensor which makes it more generally applicable in the condition where this sensor is difficult to install, especially for the high-pressure rotors of dual-rotor engines. Only three casing mounted probes are required to identify the engine order, amplitude, natural frequency and the damping coefficient of the blade. A method is developed to identify the blade which a tip-timing data belongs to without once-per revolution sensor. Theoretical analyses of resonance parameter measurement are presented. Theoretic error of the method is investigated and corrected. Experiments are conducted and the results indicate that blade resonance parameter identification is achieved without once-per revolution sensor.

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1. Introduction

Vibration parameter measurement of rotating blades in a gas turbine engine is of great importance for turbomachinery research, blade failure analysis, and blade damage prognosis [1–3]. Compared to the traditional strain gauges based vibration measurement, the blade tip-timing method is a non-contact method and it can measure vibration parameters of all blades dynamically [4,5]. This method has become an industry-standard procedure for blade vibration measurement of turbomachinery and it is applied for damage prognosis of the turbine blades [6,7]. The tip-timing method utilizes casing mounted probes to measure the arrival times of the rotating blades and the arrival times are compared to the time at which the blades would have arrived had they not been vibrating. The vibration displacement is obtained from the difference between the two times and then it is utilized to identify vibration parameters like frequency and amplitude [8].

Various methods are applied to identify the blades vibration parameters like frequency, amplitude, and stress with the tip-timing data in different conditions [8–12]. Among these methods, the single-parameter method is utilized to identify the synchronous resonance parameters like resonance rotating speed and resonance amplitude when the rotating speed of the rotor sweeps from low to high, for these parameters are closely related to the failure and damage of the blade [6,11]. The Campbell diagram of the blade is required previously for the single-parameter method cannot identify the engine order of the resonance vibration and the resonance frequency is the product of resonance rotating speed and engine order for synchronous resonance vibration. Based on this the two-parameter method is developed to identify the engine order at a

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resonance rotating speed [12]. These methods both require a once-per revolution (OPR) sensor. The sensor is mounted near the rotating axis and output a signal when detecting a mark on the axis every revolution. This OPR signal has these functions: the rotating speed is measured by the signal; the blade which a tip-timing data belongs to is identified; in many cases it is utilized as a non-vibrating disk reference to transform tip-timing data into blade vibration data [12,13].

If the OPR signal is utilized as a non-vibrating disk reference, the tip-timing result might be very noisy in the case the axial distance between the OPR sensor and the disk is long [14]. And in some cases the OPR sensor is rather difficult to install especially for the high-pressure compressor of a dual-rotor engine, whose axis is inside the engine and isolated from the axis of the low-pressure compressor. In this case the OPR sensor is rather difficult to install [15]. So a tip-timing method without OPR sensor which is more generally applicable is required to measure the blade vibration parameter dynamically in this condition. When no OPR signal is available, the rotating speed can be acquired directly from the tip-timing signals of one blade between neighboring two circles for the timing error caused by the blade vibration is very small compared to the rotating cycle time; so measurement of the rotating speed is not focused on in this article.

In this article, a blade resonance vibration measurement method which requires no OPR sensor is presented. A method on identifying the blade which a tip-timing data belongs to is presented. This method utilizes tip-timing intervals of neighboring blades and the installation errors of blades to realize the identification and requires no OPR signal. The timing difference between different casing mounted sensors of one blade is analyzed when the rotating speed is sweeping and parameter fitting based on the model of single parameter method is utilized for blade resonance parameter identification [16]. Engine order identification is realized by traversing all possible engine orders and analyzing the fitting results of different sensors. Only two casing mounted sensors are required for parameter identification of all blades if the Campbell diagram is previously known. The engine order can be obtained with one more tip-timing sensor if it is unknown before measurement. Theoretical analysis is presented, theoretic measurement error is investigated and experiments are conducted to verify the methods. The experimental resultsindicate that the blade which a tip-timing data belongs to is identified without OPR sensor and the vibration parameter measurement results are consistent with the results of traditional single-parameter methods.

2. Theoretical analysis

In order to identify blade resonance parameter without OPR sensor, the function of the OPR signal should be realized with only tip-timing signal from the casing mounted sensors. In this section, the theoretical analysis of identifying the blade which a tip-timing data belongs to, resonance parameter measurement and engine order identification is presented.

2.1. Identifying the blade which a tip-timing data belongs to

Assuming a rotor with B blades is to be measured, the blades are numbered 0 to $B\text{-}1$ (hereafter referred to as the blade serial number). When a blade arrives at the tip-timing sensor, not only the tip-timing data is acquired, but also the blade which the data belongs to should be identified. When the OPR sensor is utilized, the blade serial number is acquired by measuring the difference between the arrival times of the OPR signal and the tip-timing signal. When no OPR signal is available, the blade identification process is presented.

The blades are usually mounted on the rotor with equal intervals, and the theoretic interval between two neighboring blades is $2\pi/B$. As installation error is inevitable, assume the interval between blade i and $i+1$ is

$$\beta_i = 2\pi/B + \delta_i \quad i = 0, 1 \ldots B-1. \tag{1}$$

The δ_i is the installation error. And $\beta_{B\text{-}1}$ is the interval between blade $B\text{-}1$ and blade 0. The sequence

$$\{\delta\} = \left\{\delta_0, \delta_1 \ldots \delta_i \ldots \delta_{B-1}\right\} \tag{2}$$

can be acquired precisely before tip-timing measurement. The sequence is used as a template in the following blade serial number identification process.

In the tip-timing process, the time interval of two neighboring blades is measured and a sequence of time intervals is as follows:

$$\{t_s\} = \{\ldots t_{-k} \ldots t_{-1}, t_0, t_1 \ldots t_k \ldots\}. \tag{3}$$

Assuming the time interval t_0 is the interval between blade i and $i+1$, so

$$t_k = \frac{\beta_{\mathrm{mod}(i+k,B)} + \sigma_k}{\Omega} = \frac{2\pi/B + \delta_{\mathrm{mod}(i+k,B)} + \sigma_k}{\Omega}, \tag{4}$$

where the $mod(i+k, B)$ is the remainder of $i+k$ divided by B and σ_k represents the blade vibration and the noise in the tip-timing process. A new sequence $\{\Delta t_k\}$ is defined as

$$\{\Delta t_k\} = \{t_s\} - 2\pi/(B\Omega) = \left\{\frac{\delta_{\mathrm{mod}(i+k,B)} + \sigma_k}{\Omega}\right\}, \tag{5}$$

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