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Analysis on accuracy improvement of rotor–stator rubbing localization based on acoustic emission beamforming method

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ABSTRACT

This paper attempts to introduce an improved acoustic emission (AE) beamforming method to localize rotor–stator rubbing fault in rotating machinery. To investigate the propagation characteristics of acoustic emission signals in casing shell plate of rotating machinery, the plate wave theory is used in a thin plate. A simulation is conducted and its result shows the localization accuracy of beamforming depends on multi-mode, dispersion, velocity and array dimension. In order to reduce the effect of propagation characteristics on the source localization, an AE signal pre-process method is introduced by combining plate wave theory and wavelet packet transform. And the revised localization velocity to reduce effect of array size is presented. The accuracy of rubbing localization based on beamforming and the improved method of present paper are compared by the rubbing test carried on a test table of rotating machinery. The results indicate that the improved method can localize rub fault effectively.

1. Introduction

The rotor–stator rubbing is a hazard occurring in turbines, aircraft engines and other rotating machinery and it may cause dramatic damage or failure [1]. Since Newkirt [2] explored the thermal effect induced by rub fault of turbo machinery, the rub fault diagnosis methods have been widely appreciated and investigated [3–6]. It is well known that different rubbing may cause various types of damage of the rotor system [7], and the contact position can effectively reflect the different working conditions for turbines or aero-engines with multi-stage blades. In order to well diagnose the types and reasons of rubbing and ease of maintenance, it is necessary to determine the rubbing position accurately. By far, the most researches are focused on whether rubbing fault happens while accurate localization of rubbing is rarely seen.

Currently, vibration and acoustic emission (AE) methods are generally used to localize rotor–stator rubbing. In vibration method, the changes of stiffness [8], damping [9], mode [10] and/or other parameters of a rotor system are monitored to determine the rubbing location. Since the vibration response of rotor–stator rubbing is obviously nonlinear and it highly depends on the rubbing conditions, it is not effective to use vibration method to localize rubbing position of the rotor–stator [11]. Therefore, the probability of using AE to localize rotor–stator rubs is explored in present paper. The rotor–stator rubbing causes scratching at the rubbing location of a rotor system and generates AE signals containing lots of rubbing information and may be used to diagnose rub fault [12]. At present, some scholars have investigated rub fault detection by AE technique. Wang and Chu [13] extracted the rub fault feature through AE signal waveform analysis technology, and developed the AE rubbing positioning method based on wavelet decomposition. Hall and Mba [14,15] diagnosed the rotor–stator rubs of turbine units by using AE technology. Deng et al. [16] researched the noise reduction for rubbing AE signals in the rotating machinery. These researches indicated that the AE technique may be used to detect rotor–stator rubbing and find the rub location. It is shown in their results that the localization accuracy was improved by introducing AE technology. This technology has been demonstrated and it has beneficial prospects for applications in rubs fault diagnosis field.

Current rubbing localization methods are primarily focused on the linear localization based on the time difference of arrival (TDOA) method, which is feasible on a rubbing test table. Arrival time is the most important parameter used for source location of TDOA [17]. However, the arrival time may be significantly affected by multi-mode, dispersion, energy attenuation and other factors [18]. Hence some techniques to improve the accuracy of arrival time are developed by some researchers in past several decades. Gorman [19] introduced plate wave theory to improve the source localization by taking plate wave propagation such as modes and dispersion into account. Niri and Salamone [20] proposed a proba-

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bilistic approach to decrease the uncertainties in wave velocity and time of flight measurements. Since time delays cannot be simply estimated, Ahadi et al. [21] localized continuous acoustic emission sources by using an intelligent locator. But lots of repeated training should be done before localization by intelligent locator. Another key problem of TDOA is measuring arrival time may be confused when two or more AE sources are existed. Thus, it is worth conducting the research work to improve the accuracy of TDOA.

Some localization methods without wave velocity were presented since it is difficult to measure the arrival time accurately. For example, Ing et al. [22] proposed the time reversal technique to localize the acoustic source. This technique does not require arrival time but repeated training to keep a certain localization accuracy. How it may can take quite long time if the area of interest is very large. Hence some new AE source localization methods like beamforming were proposed. Beamforming, an array signal processing method, is carried out to measure signals with an array of sensors. It is widely used in communication, sonar, radar, noise source identification fields, etc. [23]. Compared with TDOA method, beamforming has its own advantages, such as the simplified sensor arrangement, unobvious channel attenuation, and simultaneous localization of multiple sources. McLaskey et al. [24] investigated the damage of large structures in civil engineering by using nondestructive tests based on AE beamforming method, which is the first application of beamforming in AE source localization. In previous work of the authors [25], theoretical analysis and pencil-lead-broken (PLB) localization test on steel plate have been conducted to verify the feasibility of beamforming method in AE source localization, and it is shown that AE beamforming method is a probable way to localize rub fault. Nakatani et al. [26,27] introduced the beamforming to anisotropic structure, in which the wave velocities are dependent on propagation directions. Since beamforming is a velocity-depended method in direction normal to the array [25], the source localization of AE is not as easy as the sound because AE waves in solid structures have multi-mode and dispersion. The propagation velocity of AE signals are changed with not only the directions in an anisotropic structure [28], but also the modes and frequencies of signals in an isotropic structure [25,29]. Therefore, the propagation characteristics may affect the localization accuracy of beamforming. However, the mechanism of AE propagation characteristics on the localization accuracy of beamforming has not been revealed yet. In addition, the effect of the array size has not been analyzed in AE beamforming though it is important to the accuracy of source localization.

This paper aims to improve the localization accuracy of rotor–stator rubbing by combining the AE beamforming method with the plate theory. The influence factors of localization accuracy of the beamforming method in simulation are analyzed by taking account of the multi-mode, dispersion, localization velocity and array size. And the beamforming method combining with plate wave theory and wavelet packet band energy decomposition is proposed for the pre-processing of AE signals to improve the localization accuracy of the AE beamforming. In addition, rubbing tests are carried out on a test table of rotational machinery to compare the accuracy of the AE method and the improved one with detailed discussion.

2. Theoretical fundamental

2.1. Delay-and-sum beamforming

In typical beamforming method, a set of microphone array distributed in fixed positions is used to measure the spatial sound field. The detailed information of the sound source, especially the source localization, is obtained by various signal processing methods. Based on the distance between the sound source and the array, beamforming methods are divided into far-field method and near-field one. Mailloux [30] proposed an empirical formula to describe the rule. When the distance between the sound source and the array r is satisfied with $r \leqslant 2L^2/\lambda$, the sound source can be regarded as near-field, where L and λ are the largest dimension and the wavelength of the sound source respectively. In such condition, the propagation of the sound wave should be analyzed as spherical one. For the condition of $r > 2L^2/\lambda$, the sound wave can be considered as far-field, and the propagation of the sound wave should be analyzed as plane one.

Considering the dimensions of the casing and sensors layout, the near-field beamforming method are applicable to localize the rubbing AE source. Among various beamforming algorithms, delay-and-sum is the most widely used one [31], which is simple but very effective. Since the AE signals in plate are propagated in two-dimensional space, the simple and uniformly aligned linear array is chosen in the tests.

When the array is focused to a point source at limited distance, the incident acoustic waves are spherical, as shown in Fig. 1. Array output is calculated by

$$b(\vec{r}, t) = \frac{1}{M}\sum_{m=1}^{M} w_m x_m(t - \Delta_m(\vec{r})) \tag{1}$$

where M is the number of sensors, w_m the weighting coefficient for the channel of sensor m and $x_m(t)$ the measured signal of sensor m. $\Delta_m(\vec{r})$ indicates the individual time delay of No. m sensor to the reference point. By adjusting time delay $\Delta_m(\vec{r})$, the signals associated with the spherical waves, emitting from sound source focus, will be aligned in time before they are summed. If the focused point is the real source, the signals are aligned at the same wave front and the output of the beamforming is maximum. However, the signals cannot be aligned at the same wave front when the array of sensors is focused on other positions, and the output of the beamforming is not the maximum.

As shown in Fig. 1, $\Delta_m(\vec{r})$ can be obtained by

$$\Delta_m(\vec{r}) = \frac{|\vec{r}| - |\vec{r} - \vec{r}_m|}{c} \tag{2}$$

where $\vec{r}$ represents the distance of the reference to the focus point, $\vec{r}_m$ the distance between reference point and No. m sensor, and c the propagation velocity of sound.

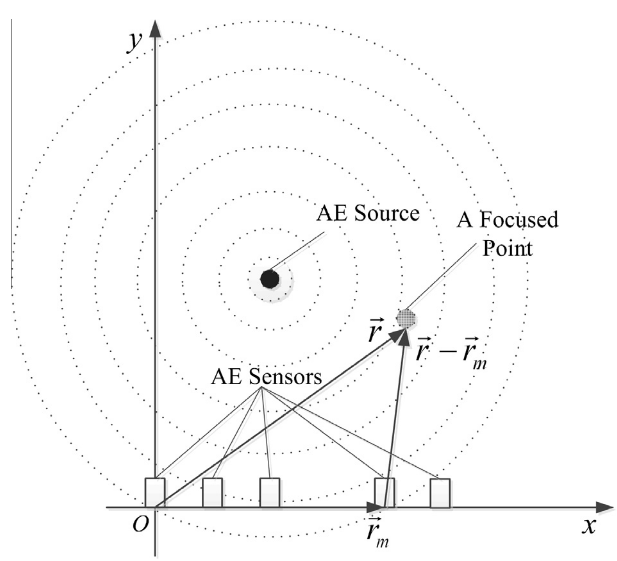

Fig. 1. Illustration of delay-and-sum beamforming.