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Numerical simulation of pressure pulsation and transient flow field in an axial flow fan

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ABSTRACT

An abnormal regulation of the stagger angle deteriorates the internal flow field and pressure pulsation, leading to an augmentation of aero-acoustic noise and vibrations in variable-pitch axial fans. To evaluate the effects of an abnormal stagger angle, the pressure pulsation and transient flow field under normal and abnormal regulations of the stagger angle were simulated using unsteady 3D modelling. The characterization capabilities of the approximate entropy and sample entropy for identifying an abnormal deviation were examined by extracting the features from the static pressure signals. The results indicate that, after an abnormal deviation of stagger angle, the periodic and quasi-periodic pulsation distributions of the static pressure are distinctly hindered, and the impacts of an abnormal deviation angle on the pressure distributions in the time and frequency domains are intensified with increasing deviation degree, resulting in increased pressure fluctuation intensity. The transient flow field clearly changes with time and degree of deviation, and abnormal high- and low-pressure regions are developed. Both the approximate entropy and sample entropy can be used to identify an abnormal blade deviation, but the sample entropy is more suitable for characterizing the effects of deviation degree on the static pressure at the impeller and guide vane outlets.

1. Introduction

A variable-pitch axial flow fan has inherently diverse merits, including a compact structure, a wide operating scope, and high efficiency under varying-load conditions; hence, it is widely employed in many engineering applications, such as the energy, mining, power, and transportation fields. In particular, a variable-pitch axial fan is a preferred choice for primary fans, induced draft fans, and forced draft fans in modern large power-generation units [1]. However, a stagger angle anomaly of one or several rotating blades induced through a mechanical fault frequently appears in varying-load processes, leading to a degradation of the operating performance, an aggravation of vibrations and noises, and even the emergence of a stall or stoppage [2]. These faults include a rotor unbalance caused by an inaccurate assembly of the balance components, a poor sliding of the gear sleeve associated with the deeper installation depth of spare bolts in the feedback apparatuses, an increased regulating resistance of a petiole bearing owing to the penetration of flyash into the bearing clearance, and a fixation anomaly between the gear sleeve and adjustment lever resulting from a bearing failure or lever break [2–4]. Previous researches have indicated that one of the important reasons for the aforementioned performance variations is a deterioration of the pressure pulsation in the unsteady flow fields induced by an abnormal deviation of the stagger angle [2–5]. Thus, it is important to investigate the characteristics of the pressure pulsation and the internally transient dynamics of such a fan with a stagger angle anomaly of the rotating blades.

Significant advances in capturing the internal flow field and pressure pulsation have been achieved both experimentally and numerically. Regarding the internal flow field, using hot wire anemometry (HWA), Chen et al. [6] conducted an experiment study on the flow field of a variable-pitch axial fan under different stagger angles and evaluated the effects of the stagger angle variation on the flow patterns at the inlet and outlet of the impeller; their results showed that the performance and surge margin are improved by regulating the stagger angle, whereas the maximum efficiency is reduced to a certain extent. Similarly, using the HWA technique, Fernández Oro et al. [7] measured the unsteady flow structure of a low-speed axial fan at different operating points and presented the

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underlying mechanism in both wake-transport phenomena and stator-rotor interactions. Zhang et al. [8] numerically simulated the transient flow field of an axial flow fan under rotating stall condition; their results showed that a stalled cell exists in the impeller, with its propagation direction being the same as the rotation direction of the impeller, and the equivalent stress distribution is greatly influenced by the centrifugal force. Nouri et al. [9] examined the effects of the rotor structure and relative axial spacing on the performance of counter-rotating axial fans both numerically and experimentally; their results showed that increasing the rotation rate ratio can improve the overall performance and steady operation domain, and that increasing the axial spacing causes only a small decrease in efficiency. Using a steady modelling approach, Ye and Li [10–11] simulated the influence of an abnormal stagger angle of single and multiple rotating blades on the aerodynamic performance and aero-acoustics of an axial flow fan; their results showed that both the aerodynamics and acoustics tend to deteriorate, and that the effect of the number of abnormal blades on the efficiency is more pronounced than that on the total pressure rise.

A variation in the transient flow field is inevitably accompanied with an alteration of the pressure pulsation. Hirata et al. [12] carried out an experiment study on an unsteady pressure on a rotating flat-blade surface of a simple cross-flow impeller in an open space without any casings. Funaki et al. [13] revealed the minute fluctuating pressure features on the 3D blade surfaces of a basic propeller fan, and illustrated the spatial distribution on the blade based on both the time-mean pressure and pressure-fluctuation intensity. Hurault et al. [14] tested the steady and unsteady wall pressure fluctuations in an automotive cooling fan, and predicted the surface-pressure power spectra using 3D Reynolds averaged Navier-Stokes (RANS) equation with Reynolds stress model and semi-empirical aero-acoustic models; their results showed that the wall pressure spectra levels simulated using the semi-empirical models are undervalued within a low frequency range of 100 to 2000 Hz, but agree quite well within a high frequency range of 2–10 kHz. Recent investigations show that the large eddy simulation (LES) method is an efficient scheme for accurately predicting highly unsteady features of transient flow fields, and the Ffowcs Williams-Hawkings (FW-H) model based on the Lighthill sound analogy was successfully applied to an estimation of aerodynamic noise [2,15–17]. Carolus et al. [16] predicted the fluctuating forces on the blades and the broadband noise of low-pressure axial fans using LES and a simple semi-empirical noise model, and the turbulence statistics were verified with HWA; their findings showed that the predicted effects of the ingested turbulence on the fluctuating blade forces and fan noise agree with the experiment results. Fernández Oro et al. [17] conducted 3D simulations of dynamic and periodic stator-rotor interactions in a low-speed axial fan using the RANS and LES techniques, and characterized the unsteady flow structures involved in an axial flow blower, as well as the mechanism related to the blade-passing frequency in a single rotor-stator interaction. Li et al. [2] assessed the effects of a deviation in the stagger angle of an abnormal blade on the aerodynamics and aero-acoustics of an axial fan using LES and FW-H models, and extracted the energy features of the sound pressure using wavelet packet decomposition (WPD) and empirical mode decomposition (EMD); their results showed that the degree of deviation of an abnormal stagger angle has a crucial influence on the range and amplitude of the sound pressure level, and that the features extracted from WPD and EMD provide important references for recognizing an abnormal angle deviation.

Although many admirable achievements on the pressure pulsation and transient flow field of axial fans have been gained over the past two decades, few studies have focused on the impact of an abnormal stagger angle of rotating blades on the aerodynamic and aero-acoustic performance of a variable-pitch axial flow fan [2,10,11]. In addition, it should be pointed out that in Li et al.'s investigation [2], noise monitoring probes were placed in the bell mouth, impeller, guide vane, and diffuser, and only the averaged total pressure distributions at the outlet stream surface and in the span-wise cross section at 10% of the blade height were presented. However, published studies have revealed that the pressure pulsations at the tip clearance of the rotating blades, as well as before and after the impeller, are extremely important sources of noise; hence, to effectively highlight the influence of an abnormal stagger angle, the monitoring probes should be arranged at key positions of a severe pressure pulsation. Additionally, transient flow fields were not provided in the results of Li et al. [2], and thus the effect of an abnormal blade on the variation of the transient flow field and the characterization of the pressure pulsation are not well understood. Therefore, for such an axial fan under an abnormal regulation of the stagger angle, some crucial characteristics including the pressure pulsation and transient flow field at the key positions and cross sections, as well as a characterization of the pressure pulsation feature, need to be further investigated.

This paper is organized as follows: an axial fan model is described in Section 2; the numerical methodology is elaborated in Section 3. The distributions of pressure pulsation and transient flow field, and the characterization of pressure pulsation with the approximate entropy and sample entropy are discussed in Section 4. Finally, the conclusions of this work are summarized in Section 5.

2. Formulation of fan model

In the present modelling, a OB-84 type variable-pitch axial fan was used to explore the effects of an abnormal stagger angle of a single rotating blade on the pressure pulsation and transient flow fields. The axial fan model consists of four components: a bell mouth, an impeller, an outlet guide vane, and a diffuser, as shown in Fig. 1. The crucial characteristics are given as follows: (1) the fan has 14 rotating blades and 15 guide vanes, (2) the impeller diameter and tip clearance are 1500 and 4.5 mm, respectively, (3) the fan is driven at a constant rotating speed of 1200 rpm, (4) under the design conditions, the normal stagger angle of the rotating blades is 32°, and the volumetric flow rate and total pressure rise are 37.12 m^3/s and 2254 Pa, respectively, and (5) the blade-passing frequency is 280 Hz. The fan performance curves under three blade angles of 29°, 32°, and 35° are given in Ref. [18], and were used to assess the accuracy and reliability of the present modelling.

The aero-acoustics of an axial flow fan is mainly dominated by the pressure pulsation and internal unsteady flow. An abnormal

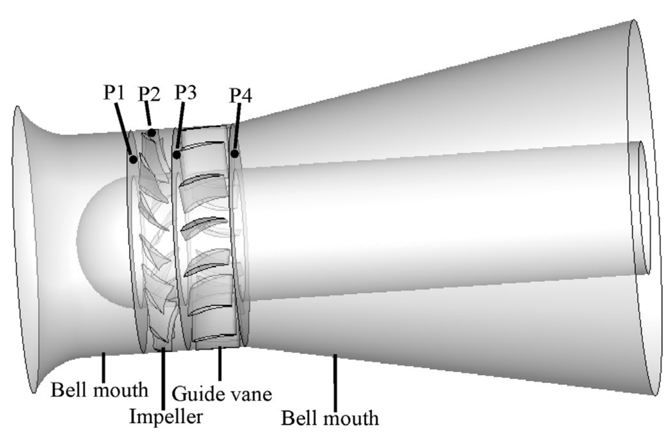

Fig. 1. Diagram of fan structure and arrangement of monitoring probes.