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Energy dissipation in the blade tip region of an axial fan

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ABSTRACT

A study of velocity and pressure fluctuations in the tip clearance flow of an axial fan is presented in this paper. Two different rotor blade tip designs were investigated: the standard one with straight blade tips and the modified one with swept-back tip winglets. Comparison of integral sound parameters indicates a significant noise level reduction for the modified blade tip design. To study the underlying mechanisms of the energy conversion and noise generation, a novel experimental method based on simultaneous measurements of local flow velocity and pressure has also been developed and is presented here. The method is based on the phase space analysis by the use of attractors, which enable more accurate identification and determination of the local flow structures and turbulent flow properties. Specific gap flow energy derived from the pressure and velocity time series was introduced as an additional attractor parameter to assess the flow energy distribution and dissipation within the phase space, and thus determines characteristic sources of the fan acoustic emission. The attractors reveal a more efficient conversion of the pressure to kinetic flow energy in the case of the modified (tip winglet) fan blade design, and also a reduction in emitted noise levels. The findings of the attractor analysis are in a good agreement with integral fan characteristics (efficiency and noise level), while offering a much more accurate and detailed representation of gap flow phenomena.

1. Introduction

A good quality axial fan is characterized by efficient conversion of mechanical energy into the energy of fluid and by low emitted noise. However, the relation between the energy conversion efficiency and emitted noise level is not always straightforward, and it is challenging to improve both while also assuring reliable fan operation. The region in the gap between the fan blade tip and case housing remains one of the most important sources of fluid energy dissipation due to the leakage flow, i.e. air-gap flow from the pressure to the suction side of the fan blade [1]. As the leakage flow merges with the main (central) blade airflow, induced vortices are formed and gradually disintegrate into smaller coherent structures, which is also an important noise generation mechanism [1].

The air-gap leakage was first described by Rains [2], Varva [3] and Senoo and Ishida [4] based on the theoretical pressure distribution at the blade tip. Lakshminarayana and Horlock [5] modeled the swirling of the airflow past the blade tip as the

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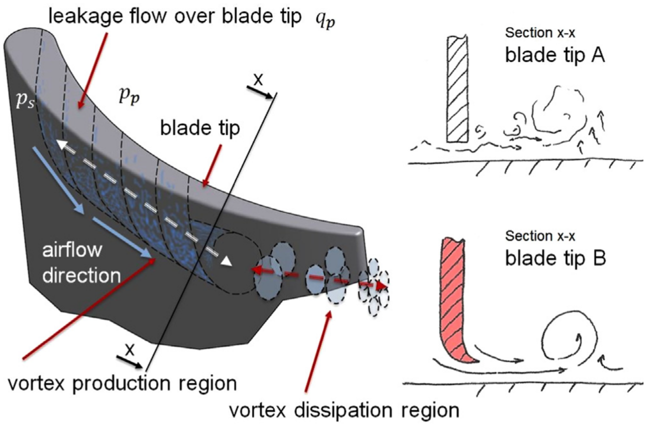

Fig. 1. Design of the tested blade tips A and B, and related flow phenomena.

potential swirl in order to describe induced flow resistance and make a rough estimation of the pressure losses in the blade channel. The model was later improved and experimentally evaluated by Gusakova et al. [6], Mehmed [7] and Inoue et al. [8]. The leakage flow across the blade tip was also identified as a predominant source of the wideband noise [9–11]. Pressure and velocity measurements within the blade tip gap confirmed the presence of low frequency fluctuations (i.e. lower than the blade rotation frequency) which were linked to the phenomenon of the flow separation on the blade tip.

Subsequent research was focused on the influence of the blade tip shape design on reduction of the gap flow intensity and consequent reduction of the swirly motion behind the blade tip. Corsini et al. [12,13] proposed to add profiled end-plates to the blade tips, while Moreau and Sanjose [14] experimentally and numerically investigated a design with a full ring connecting individual blade tips. Another blade tip design which has been a subject of recent studies [15–17] and has also been successfully implemented in industrial production [18] is by tip winglets which are swept-back to the suction side of the blade. Apart from the blade tip, the shape of the blade profile can also be modified to reduce the effect of leakage flow, for example by a rib-like structure to channel the leakage jet towards a more desirable direction [19]. Another important parameter for controlling the extent of the leakage flow is the airfoil's angle of attack [20], but on axial fan blades it cannot be changed in a very wide range without negatively affecting the fan efficiency. In this paper, only the winglet-type modification of blade tips will be investigated with respect to the basic straight blade tip design (design B and A, respectively).

The kinematics of the leakage flow and its dissipation is shown schematically in Fig. 1 for both A and B blade tip designs, along with the typical blade tip shape in the transverse section ($x-x$). The leakage flow q_p between the pressure (p_p) and suction (p_s) side of the blade presents, together with induced vortices, a mechanism of fluid energy dissipation in the blade tip region [5]. In our previous research [15–17], we have confirmed a significant effect of the blade tip clearance and geometry on the aerodynamic and acoustic characteristics of axial fans. In addition, local pressure fluctuations and emitted noise levels were determined to have a significant correlation [15–17]. The modifications of the blade tip geometry (i.e. addition of winglets) were shown to affect the local airflow kinematics in the tip region, which was reflected by the emitted sound pressure magnitude and frequency distribution in the power spectrum [16,17]. Based on known integral fan characteristics and local measurements of airflow velocity and pressure, this paper will investigate the mechanism of flow energy conversion and dissipation depending on the operating conditions and blade tip geometry of the observed fan.

The paper is organized as follows. The experimental setup used for the measurements of local and integral fan operating characteristics will be presented in Section 2. Integral fan characteristics (efficiency and noise level) will also be discussed in this section. Section 3 will first present the results of the sound pressure spectral analysis. Then, a time series analysis will be performed, and characteristic gap flow phenomena will be identified. In the next step, the gap energy flow will be presented in the form of attractors by showing simultaneously measured fluctuations of fluid static pressure and velocity in the phase space. This analysis aims to explain the difference in the energy dissipation and noise generation mechanism between both investigated blade tip designs. Finally, our findings will be summarized in the Conclusion section.

2. Experimental set-up

An axial fan manufactured by Hidria d.d. (type R11R-63LPS-ECM-3501 [21]) was selected for investigation of the blade tip shape effect. Fan blade geometry was based upon the NACA airfoil calculation model with the shape parameters defined by the manufacturer Hidria. In performed experiments, variation of the fan blade geometry was possible by replacement of the blade upper part (i.e. the blade tip). The blade tip design A (Fig. 1, left) was formed by extension of the basic blade geometry up to the tip of the blade, while the design B was uniformly curved towards the suction side of the blade, forming a winglet. The average minimum clearance d_0 between the fan tip and the casing was the same for both blade tip designs. Technical

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