Journal of Sound and Vibration 417 (2018) 198–215

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Rotating coherent flow structures as a source for narrowband tip clearance noise from axial fans

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ARTICLE INFO

Article history:
Received 21 July 2017
Revised 13 October 2017
Accepted 9 November 2017
Available online XXX

Keywords:
Aeroacoustics
Axial fans
Tip gap flow
Lattice-Boltzmann method
Modal analysis

ABSTRACT

Noise from axial fans typically increases significantly as the tip clearance is increased. In addition to the broadband tip clearance noise at the design flow rate, narrowband humps also associated with the tip flow are observed in the far-field acoustic spectra at lower flow rate. In this study, both experimental and numerical methods are used to shed more light on the noise generation mechanism of this narrowband tip clearance noise and provide a unified description of this source. Unsteady aeroacoustic predictions with the Lattice-Boltzmann Method (LBM) are successfully compared with experiment. Such a validation allows using LBM data to conduct a detailed modal analysis of the pressure field for detecting rotating coherent flow structures which might be considered as noise sources. As previously found in ring fans the narrowband humps in the far-field noise spectra are found to be related to the tip clearance noise that is generated by an interaction of coherent flow structures present in the tip region with the leading edge of the impeller blades. The visualization of the coherent structures shows that they are indeed part of the unsteady tip clearance vortex structures. They are hidden in a complex, spatially and temporally inhomogeneous flow field, but can be recovered by means of appropriate filtering techniques. Their pressure trace corresponds to the so-called rotational instability identified in previous turbomachinery studies, which brings a unified picture of this tip-noise phenomenon for the first time.

1. Introduction

The aerodynamic and aeroacoustic performance of axial fans are strongly influenced by the tip clearance flow [1–6]. Typically, aerodynamic losses and sound radiation increase significantly with larger tip clearances for a given design. For instance, recent studies based on an axial fan with a classical tip clearance (experimental and numerical investigations by Zhu and Carolus [7,8]) have shown that at the design point, the strong tip clearance vortices induced by a large tip gap ($s/D_a = 1.0\%$ with s the tip-gap height and D_a the duct diameter) interact with the fan blade surfaces, which generally produces broadband tip clearance noise. At lower flow rates, narrowband humps associated with tip clearance noise are also observed in the acoustic spectra measured in the far field. Similar issues regarding the tip clearance flow of an axial fan with a large tip gap were also investigated by Kameier and Neise [9], März [10] and more recently Pardowitz *et al.* [11,12], who suggested that this kind of narrowband hump in the acoustic spectra could be attributed to a so-called "Rotating Instability" (RI) developing in the blade tip region. Similar observations were reported in the case of an axial ring fan, even at design condition: first on the fan-alone flush-mounted test

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https://doi.org/10.1016/j.jsv.2017.11.014
0022-460X/

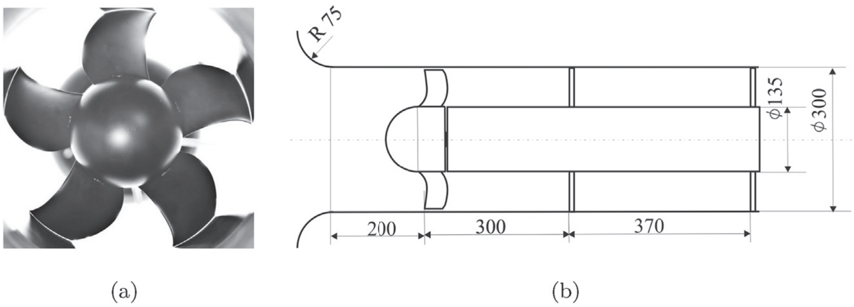

Fig. 1. Tested configuration: (a) manufactured impeller; (b) fan installation in duct (dimensions in mm).

rig by Magne *et al.* [13] and Moreau and Sanjosé [14], and later on a complete engine cooling module by Piellard *et al.* [15] and Lallier-Daniels *et al.* [16,17]. All these configurations involved highly loaded fans at the tip with significant tip flow features. The noise mechanism was explained as the interaction between coherent structures forming in the tip region ahead of the fan and originating from the backflow from the ring gap with the fan blades.

The object of the present work is to shed more light on the noise generation mechanism for this narrowband tip clearance noise using both experimental and numerical methods. Employing unsteady simulations based on the Lattice-Boltzmann-Method, a comprehensive modal analysis can be carried out to detect rotating coherent flow structures induced from the complex and unsteady tip clearance flow, which are construed as the mechanism for the identified narrowband humps. Preliminary results have been shown by Zhu *et al.* [18].

2. Experimental investigation

2.1. Investigated fan setup

An axial fan impeller, shown in Fig. 1(a), was designed with an in-house blade element momentum based design code for low pressure axial fans (dAX-LP [19]). Instead of having a free vortex design, the blade loading is 70% at hub and 120% at tip, distributed approximately linearly in the spanwise direction. The additional loading of the blade tip is done intentionally to provoke strong secondary tip flow that is eventually responsible for tip clearance noise. Further design parameters are compiled in Table 1. The corresponding axial Mach number $M_x \equiv V_x/c_0$ (V_x mean axial speed and c_0 speed of sound) in the duct is 0.01. Its effect on acoustic mode propagation is therefore negligible. Two impellers with different diameters were manufactured, providing a variation of tip clearance; one with a large tip clearance ratio $s/D_a = 1.0\%$ (i.e. a clearance of 3 mm) and one with an extremely small gap of $s/D_a = 0.1\%$ (i.e. a clearance of 0.3 mm). As shown in Fig. 1(b) thin supporting struts were mounted one duct diameter downstream of the rotor, so that rotor/strut interaction was minimized.

2.2. Overall aerodynamic and aeroacoustic measurements

The aerodynamic fan performance was determined on a standard plenum test rig for fans according to the ISO 5801 standard (German DIN 24163). Given that Δp_{ts} is the total-to-static pressure rise, $\dot{V} \equiv V_x S_a$ the volumic flow rate ($S_a \equiv \pi\, D_a^2/4$ the duct interior surface) and M the true rotor torque applied, the following non-dimensional fan performance coefficients are used:

The flow-rate coefficient

$$\phi = \frac{\dot{V}}{\frac{\pi^2}{4} D_a^3 n} \tag{1}$$

the total-to-static pressure-rise coefficient

$$\psi_{ts} = \frac{\Delta p_{ts}}{\frac{\pi^2}{2} \rho D_a^2 n^2} \tag{2}$$

Table 1
Important impeller design parameters.

Duct Diameter	D_a	[mm]	300	Design Flow Rate	ϕ	[–]	0.195
Hub to Tip Ratio	ν	[–]	0.45	Density of Air	ρ	[kg/m^3]	1.2
Number of Blades	z	[–]	5	Rotational Speed	n	[rpm]	3000