THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN THERMO AND FLUID DYNAMICS

Numerical investigation of tonal noise sources from centrifugal fan

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Abstract

Heating, ventilating, and air conditioning systems (HVAC) are today an important part of many people's life. They provide a sufficient amount of airflow with the correct temperature, quality, and humidity. The negative side is the noise it produces. Many improvements have been made in building development to reduce noise from the environment. When so, the noise from the HVAC system becomes clearer. The dominant tonal noise in an HVAC system is produced by the fan. In this work tonal noises produced by a centrifugal fan is investigated to be able to understand the generation mechanism and identify their sources. The approach is to use the hybrid computational aeroacoustics (CAA) method, that couples a computational fluid dynamics (CFD) method with the Ffowcs Williams and Hawkings (FW-H) acoustic analogy.

Recirculating flows, which are responsible for reducing the fan efficiency and increasing the noise generation, are observed between the shroud and the blade trailing edges. It is found that the recirculating flows are associated with the gap between the shroud and the inlet duct. The recirculating flow causes large modeled turbulence kinetic energy (TKE). The TKE is unevenly distributed among the blades due to the unsteady recirculating flow. Moreover, the position of the largest TKE periodically varies among the blades. The period corresponds to approximately 4 times the fan rotation period, it was also found in acoustic measurements.

Different pressure distributions among the blades are found and ascribed to the turbulence initializing from the inlet gap. The turbulence develops along the shroud wall and interacts with the blades at their leading edges. The interaction renders uneven surface pressure distributions among the blades as well as significant peak differences. As the distances to the inlet gap and the shroud increases, the difference of the pressure distributions among the blades decays. The wall-pressure fluctuations indicates that the locations of the tonal noise sources agree with the locations of the uneven surface pressure distributions and the significant pressure peaks, which are near the blade leading edges.

Keywords: Computational Aeroacoustics, Tonal Noise, Blade Passing Frequency, Centrifugal Fan

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List of abbreviations

Abbreviations

HVAC	– Heating, Ventilating, and Air Conditioning
AHU	– Air Handling Unite
BPF	– Blade Passing Frequency
CFD	– Computational Fluid Dynamics
CAA	– Computational Aeroacoustics
TKE	– Modeled Turbulence Kinetic Energy
PSD	– Power Spectral Density
SPL	– Surface Pressure Level

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	Ottersten M, Yao H.D, and Davidson L. Unsteady Simulation of tonal noise from isolated centrifugal fan. *Conference paper FAN2018*. Darmstadt, Germany, 2018
Paper B	Ottersten M, Yao H.D, Davidson L. Numerical and experimental study of tonal noise sources at the outlet of an isolated centrifugal fan. *Submitted to a scientific journal* (2019)
Paper C	Ottersten M, Yao H.D, Davidson L. Abrupt Increase of Centrifugal Fan Tonal Noise due to Turbulence Stemming from Inlet Gap at Off-Design Point. *To be submitted to a scientific journal (2020)*

Content

1 Introduction

1.1 Background

Sound quality is an important factor for evaluating a comfortable environment, for example in a concert. Moreover, noise is potentially a remarkable source of illness. The world health organization (WHO) reported that noise can induce hearing impairment, heart disease, poor human performances in cognitive tasks, and aggressive behaviors, etc. [1]. In particular, long-term exposure to tonal noise affects the autonomous and hormonal systems of the human body, leading to diseases such as high blood pressure, hearing loss, cardiac arrest, and mental disorders (aggressiveness and mood swings) [2].

Today people spend a large amount of time indoors. As building materials and structures have significantly improved to isolate the external noise (e.g., the traffic noise from cars and airplanes), the indoor noise from heating, ventilating, and air conditioning systems (HVAC) becomes more perceivable [3]. The indoor noise annoyance is evaluated in terms of loudness and spectral characteristics [4]. Tonal and broad noise are recognized based on noise spectral characteristics. In consideration of the harmful effects of the total noise [2], its reduction is of great interest to HVAC system manufacturers. An existing reduction method is to install silencers. However, the devices increase the hydrodynamic losses that consume additional energy.

1.2 The noise of the HVAC system

One of the functions of HVAC systems is to provide airflow. Controlling the temperature, the quality, and the humidity in the airflow is highly important. An air handling unit (AHU) is designated for the controlling. It moves and cleans air, as well as recovers latent and sensible heat in the air. As illustrated in Figure 1, a modern AHU usually consists of a fan, a filter, and two channels such as a supply and an extract. The fan is of the centrifugal type running at low speeds, to satisfy the requirements on small size and high pressure airflow [5]. The turbulent flow induced by the rotating fan emits noise in buildings [6]. The noise has both broadband and tonal parts. A typical mechanism of the tonal noise generation is the interaction between turbulent flow and rotating blades at the blade passing frequency (BPF) [7]. In addition, another type of potential tonal noise sources is coherent flow structures like those in vortex shedding.

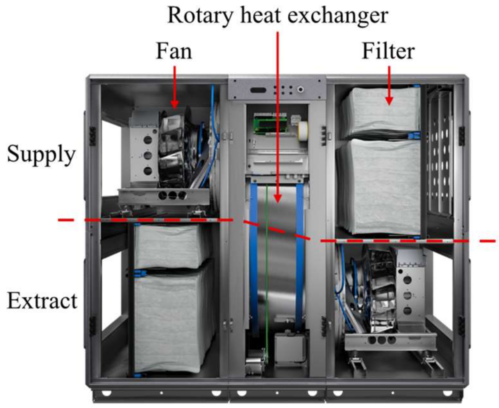

Figure 1. Swegons AHU - Gold 12 RX.

1.3 Centrifugal fan

The tonal noise in an AHU is mainly produced by the fan component. Therefore, the present study is organized to specifically investigate an isolated fan, i.e. without diffusers, guide vanes, and volutes. The fan is of the centrifugal type and operates at low rotational speeds. The numerical setup for the fan is illustrated in Figure 2. There are two ducts, which are placed upstream and downstream of the fan. The flow at the inlet is undisturbed with a uniform velocity profile. There is a gap between the stationary inlet duct and the rotating fan. Air passes through this gap into the fan due to pressure differences.

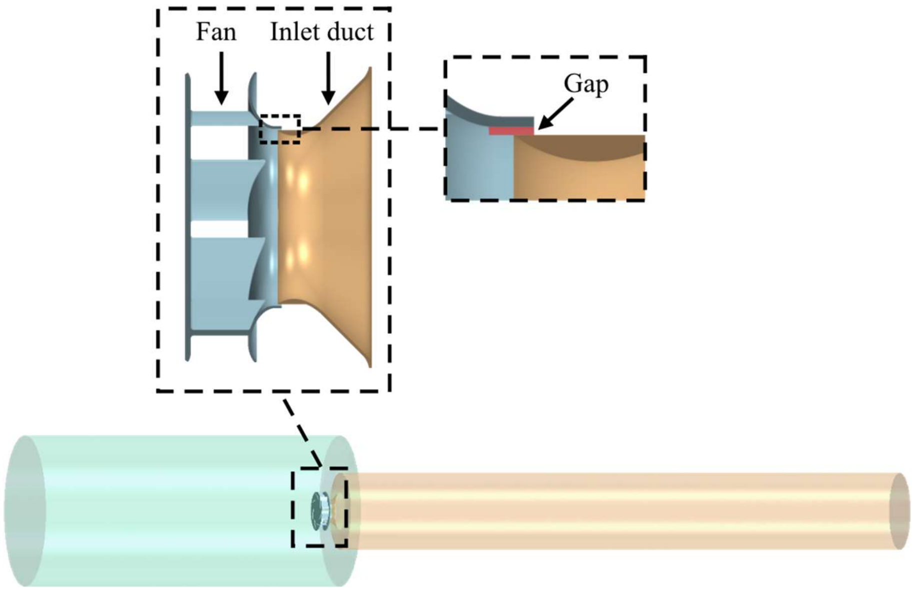

Figure 2. The fan configuration. The gap is illustrated in red.

1.4 Aim

This study is aimed at developing a hybrid computational aeroacoustics (CAA) method to accurately predict the fan tonal noise, in particular, at BPF. Moreover, the mechanisms of the tonal noise generation will be explored. The noise sources will be identified. The hybrid CAA method couples a computational fluid dynamics (CFD) method with the Ffowcs Williams and Hawkings (FW-H) acoustic analogy. The options of the CFD method are the unsteady Reynolds averaged Navier-Stokes (RANS) equations and improved delayed detached eddy simulation (IDDES). Formulation 1A of the FW-H acoustic analogy is chosen. The CAA method will be validated based on experiments.

2 Methods

Understanding and predicting tonal noise is not easy since the noise has much lower energy than the flow. A convenient method is to use acoustic analogy. The acoustic analogy was first proposed by Lighthill [8]. The basic principle of the acoustic analogy is to separate the computation of the noise generation and propagation from the flow simulation. The theory has been developed into a family of methods, in which the FW-H analogy is the most popular one. In this study, a hybrid approach coupling various CFD methods with the FW-H analogy is employed. The unsteady flow field is simulated using the unsteady RANS [9] and the Improved Delayed Detached Eddy Simulation (IDDES) [10]. The FW-H analogy is implemented with Formulation 1A [11].

2.1 URANS

The URANS method is used in the first part of this study (Paper A and B). The flow is incompressible. The turbulence is modelled using the k-ω shear-stress transport (SST) model. The segregated flow solver is used to solve the discretized equations. The pressure-velocity coupling approach is adopted for the SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations-Consistent) algorithm. A bounded second-order implicit method is used to discretize the time derivative. The simulations are performed using the software ANSYS Fluent [9].

2.2 IDDES

The IDDES method is used in the second part of this study (Paper C), the simulations are performed using the software STAR-CCM+ [10]. The flow is compressible. IDDES is combined with the k-ω SST turbulence model. The switch between RANS and LES is performed with a modified sink term in the transport equation for turbulence kinetic energy. The method employs a segregated flow solver that is accomplished with the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm. A second-order implicit method is used to discretize the time derivative. The time marching procedure adopts inner iterations at every preconditioned pseudo time step.

2.3 The FW-H acoustic analogy

A hybrid approach is adopted to predict the noise generated from the flow induced by the fan. In this hybrid approach, URANS or IDDES is coupled with the FW-H acoustic analogy. The Farassat 1A formulation of the FW-H acoustic analogy is used [12].

According to the study by Neise [13], dipole noise sources are dominant in fan noise generation at low Mach numbers. Hence, only the dipole terms in Formulation 1A are considered in this study. An impermeable surface is set on the fan surfaces including the blades, the back plate, and the shroud.

3 Results

3.1 Paper A

The fan performance is influenced by the flow separation on the blades. The separation is identified based on wall shear stress. Figure 3 shows that there is recirculating flow between the blade and the shroud. Low wall shear stress is observed near the blade trailing edge. Furthermore, it is found that the recirculating flow originates from the fan gap, as illustrated in Figure 4.

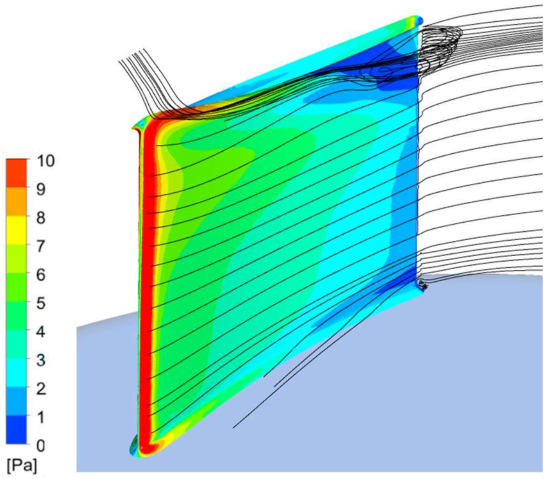

Figure 3. Contour plot of the wall shear stress at the blade with airflow visualized with streamlines

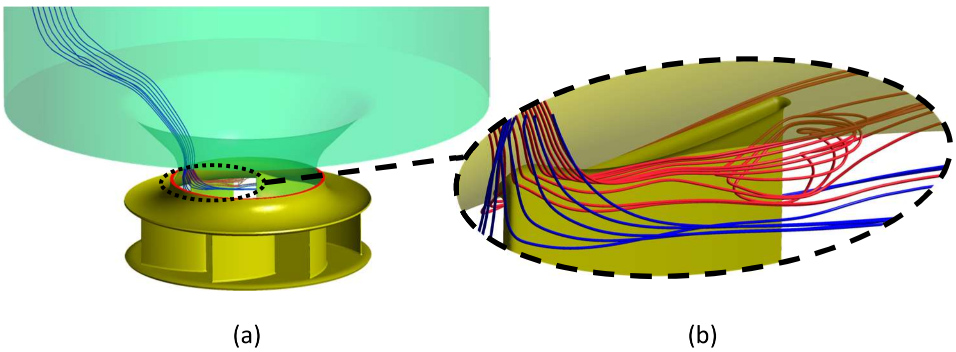

Figure 4. Streamlines starting from the inlet (blue) and the gap (red). The gap is shown in Figure 1. a) The fan and inlet duct, b) A magnified view of the blade and shroud intersection.

3.2 Paper B

Regions with high modeled turbulence kinetic energy (TKE) are found between the blade trailing edges and the shroud. These regions are associated with the recirculating flow found in Paper A (see Figure 3).

Figure 5 shows snapshots of the TKE in an axial section crossing the recirculating flow regions as well as the velocity magnitudes in the gap. Here T is the fan rotation period. The

TKE is unevenly distributed among the blades. It is observed that the largest TKE region appears at different blades periodically. As regards the blade colored in green in Figure 5, the largest TKE is shown at t_0 and $t_0 + 4T$. It is therefore concluded that the revolution period of the largest TKE region is $4T$. Moreover, the region with high velocity magnitudes always occur upstream of the blade with high TKE. This phenomenon is explained based on the streamlines illustrated in Figure 4. The streamlines passing through the fan gap become recirculating near the blade trailing edge. The large TKE could be linked to a meridional curvature effect [14]. The effect is that the flow changes the axial direction to the radial direction.

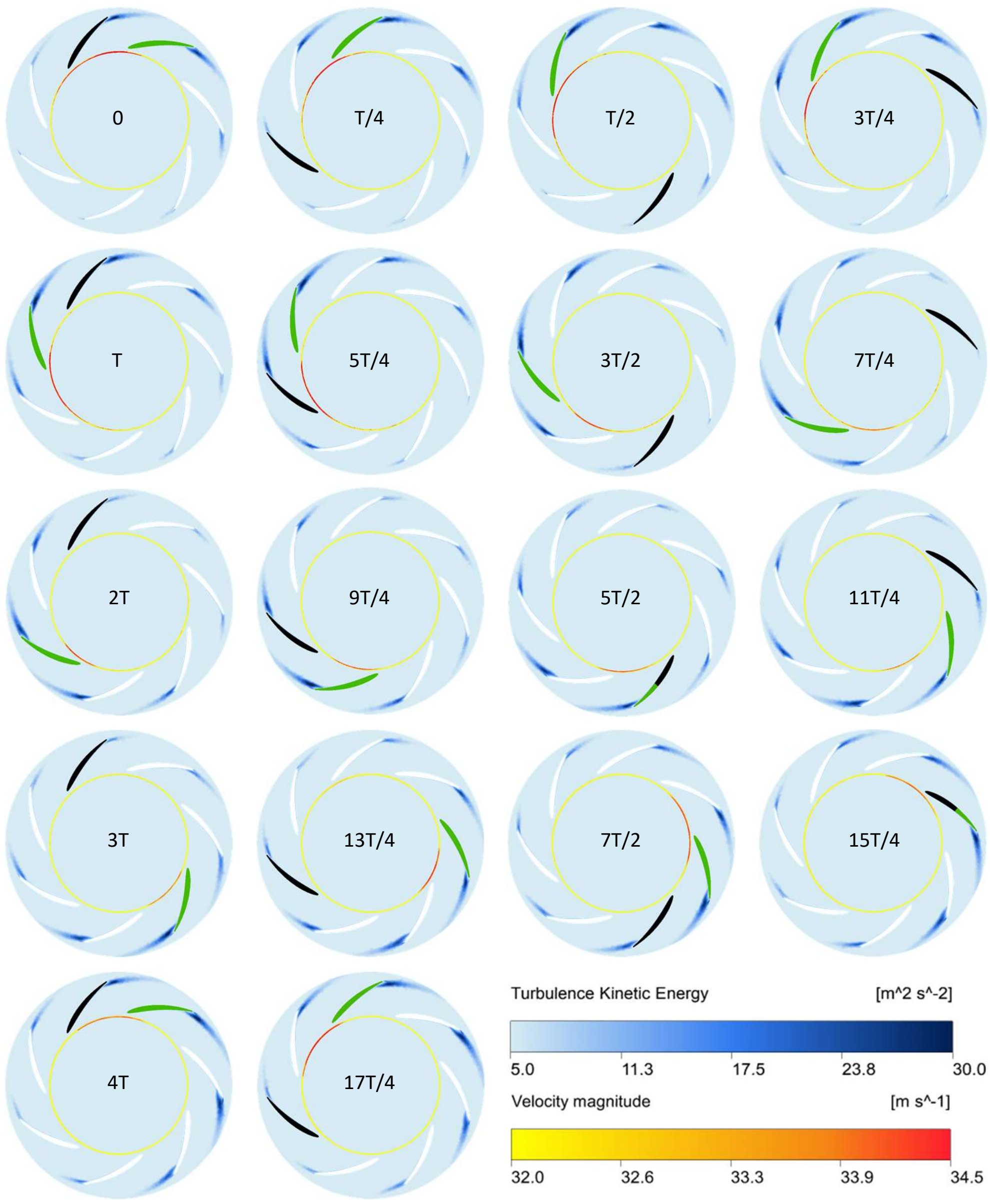

Figure 5. Snapshots of the turbulence kinetic energy in an axial section, which crosses the recirculating flow near the blade trailing edge, and the velocity magnitudes in the gap. The reference blade indicating the fan revolution is colored in black. The blade colored in green indicates the region with the largest modeled TKE.

Figure 6 presents the measured power spectral density (PSD) of the noise pressure at the microphone upstream of the fan (M1) and the downstream microphone (M2). Two tones are observed at 1/4 of BPF_0 and 1/4 of the fan rotation frequency n_f. The tones are explained in relation to the revolution period of the largest TKE region, which is $4T$ as indicated in Figure 5. This confirms the consistence of the results between the experiments and simulations.

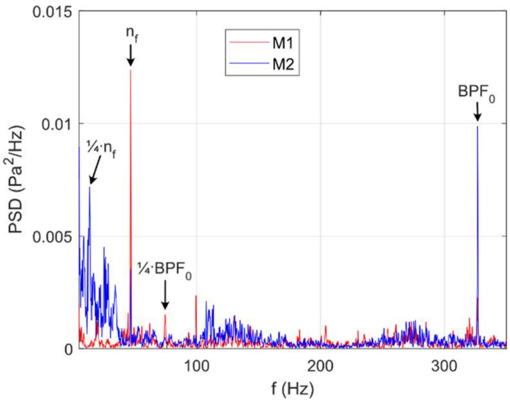

Figure 6. PSD measured in the experiment, where the microphone upstream of the fan is M1 and the downstream one is M2.

The contours of the surface pressure spectra within the frequency band between 325 and 328 Hz are illustrated in Figure 7. Note the fundamental blade passing frequency BPF_0=326.7 Hz. The spectra are scaled in sound pressure levels (SPL). Large SPL is observed near the trailing edges on the blade suction sides i.e. the recirculating flow region.

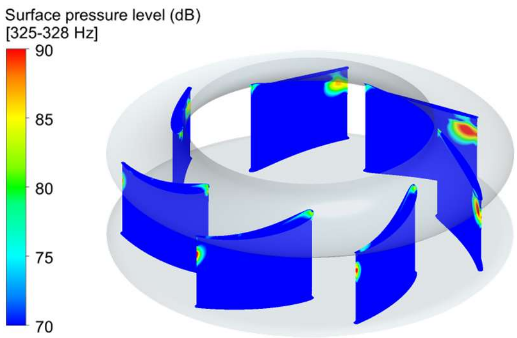

Figure 7. The surface pressure level in the frequency band between 325 and 328 Hz. Note BPF_0 = 326,7 Hz.

3.3 Paper C

Compared with the mesh used in Paper A and Paper B, the mesh is refined in all regions and especially in the gap and the blade regions. Turbulence develops from the gap between the rotating fan and the stationary inlet duct, as indicated by visualizing vorticity magnitudes near the gap in Figure 8. The result is consistent with the finding in Paper B.

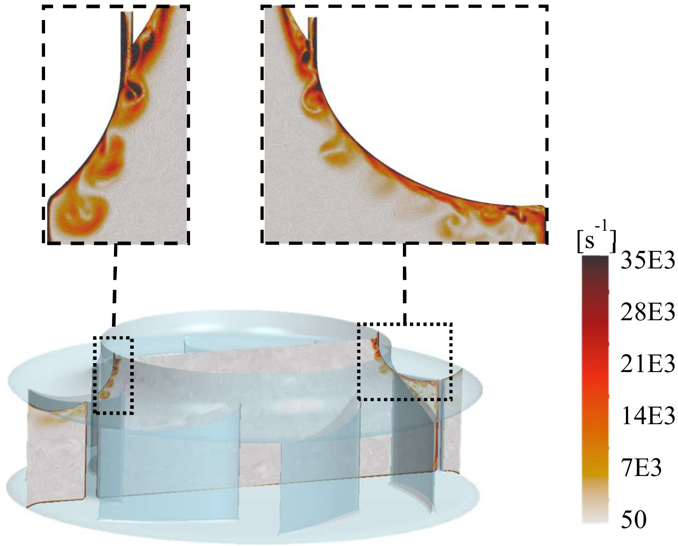

Figure 8. Instantaneous vorticity magnitude near the inlet gap.

The instantaneous surface pressure on the blade leading edges at different fan axial positions are shown in Figure 9. At the position nearest the inlet gap, a remarkable pressure peak is seen at Blade 5, but the peaks at the other blades are similar. The pressure distributions on the suction sides of the blades are obviously different at the position near the shroud. However, the differences are small at the positions that are far from the shroud. As the distances to the inlet gap and the shroud increases, the difference of the pressure distributions among the blades decays.

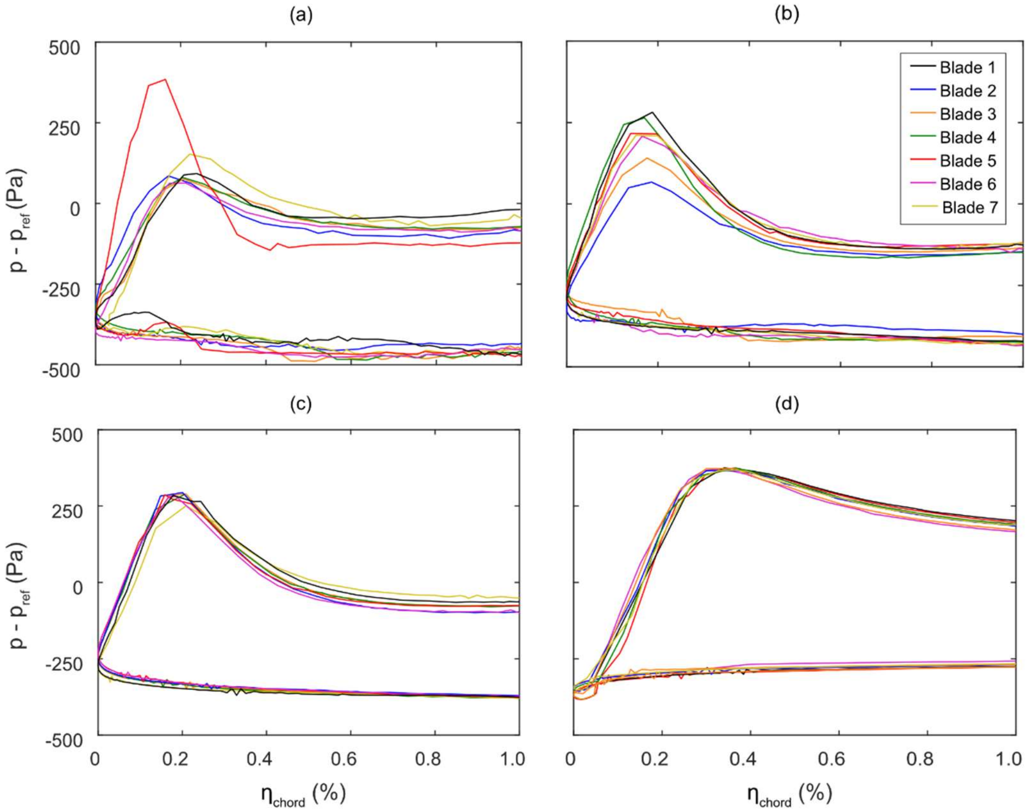

Figure 9. The instantaneous surface pressure on the blade leading edges: a) Plane 1 closest to the inlet gap, b) Plane 2 intersecting with the fan shroud, c) Plane 3 without the intersection to the shroud, and d) Plane 4 near the fan back plate, which is furthest from the inlet gap.

Based on the band filtered PSD of the wall pressure fluctuations, it is possible to find the noise sources. The surface pressure levels (SPL) at the tonal frequencies, $273\ Hz$, $326.7\ Hz\ (BPF_0)$, and $653.3\ Hz\ (BPF_1)$ are illustrated in Figure 10. The highest PSD at all tonal frequencies are located at the blade leading edge close to the shroud.

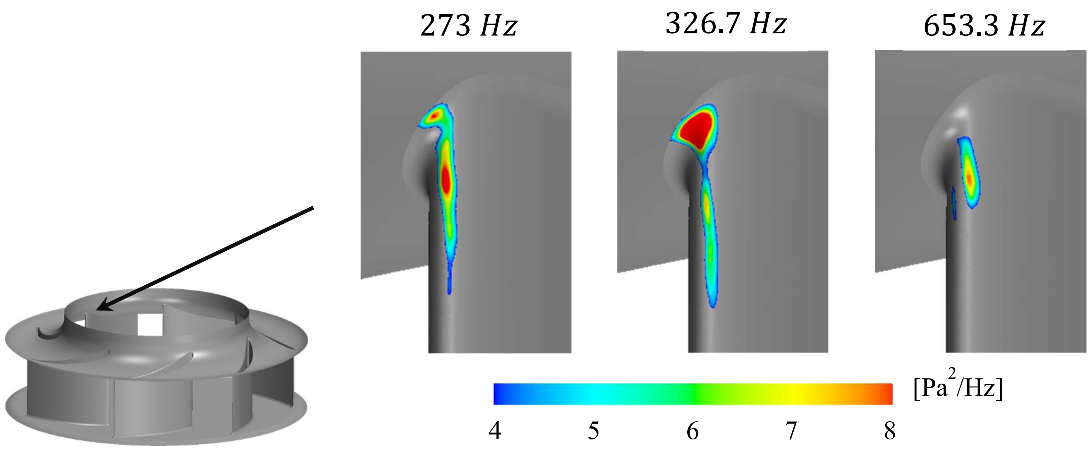

Fig. 10. SPL of the surface pressure fluctuations at three tonal frequencies

4 Conclusion

Flow recirculation is found at the suction side of the blade close to the shroud. It is associated with the gap between the shroud and the inlet duct. The recirculating flow can influence the fan efficiency and generate tonal noise.

Regions with high modeled turbulence kinetic energy (TKE) are found between the shroud and the blade trailing edge on the blade suction side. These regions are connected to the recirculating flow, which originates from the inlet gap. The TKE is unevenly distributed among the blades due to the unsteady recirculating flow. The largest TKE occurs at different blade with a revolution period of approximately $4T$, where T is the revolution period of the fan. The velocity magnitudes in the gap and the total pressure on the shroud create the high TKE. Their revolution periods are also $4T$. This revolution period is also found in the acoustic measurements in the test rig, where tonal frequencies were found at 1/4 of BPF_0 and 1/4 of the fan revolution frequency n_f.

Different pressure distributions among the blades are found and ascribed to the turbulence originating from the inlet gap. The turbulence develops along the shroud wall and interacts with the blades at their leading edges. The interaction renders the uneven surface pressure distributions among the blades as well as the significant peak differences. The peak values are related to the intensive levels of the resolved turbulence. As the distances to the inlet gap and the shroud increases, the difference of the pressure distributions among the blades decays. The reason is that the resolved turbulence from the inlet primitively develops along the shroud. The influence of the turbulence on the blades is, therefore, effective near the shroud.

The wall-pressure fluctuations indicates that the locations of the tonal noise sources $273\ Hz$, BPF_0 and BPF_1 agree with the locations of the uneven surface pressure distributions and the significant pressure peaks, which are near the blade leading edges.

Two types of tonal noise sources are found in Paper B and Paper C. The sources near the blade trailing edges are identified in Paper B, and the sources near the leading edges in Paper C. The leading edge sources cannot be resolved in Paper B. The reason is that the URANS method with a poor mesh quality is unable to resolve the vortex shedding that develops from the inlet gap.

Reference

[1] Berglund B, Lindvall T, Schwela D. New Guidelines for Community Noise. Noise & Vibration Worldwide 2000;31:24-29.

[2] Rossi A.M. Burden of disease from environmental noise Quantification of healthy life years lost in Europe, Annali dell'Istituto Superiore di Sanita, 2011;47:480.

[3] Azimi M, Noise Reduction in Buildings Using Sound Absorbing Materials. Journal of Architectural Engineering Technology 2017; 6

[4] Wang L.M, Novak C.C. Human performance and perception-based evaluations of indoor noise criteria for rating mechanical system noise with time-varying fluctuations. ASHRAE Transaction, 2010;116:553-568.

[5] Tautz M. Aeroacoustic Noise Prediction of Automotive HVAC System. FAU Forschungen, Reihre B, Medizin, Naturwissenschaft, Technik Band 27. Erlangen: FAU University Press 2019.

[6] Jones W. P. Air conditioning applications and design. 2 ed. Arnold 1997:294-295.

[7] Wolfram D, and Carolus T. H. Experimental and numerical investigation of the unsteady flow field and tone generation in an isolated centrifugal fan impeller. Journal of Sound and Vibrations 2010;329:4380-4397.

[8] Lighthill M.J. On Sound Generated Aerodynamically. I General Theory. Proc. R. Soc. Lond. A 1952;211:564-587.

[9] Ansys Inc. Fluent User Guide (Version 19.0) 2018.

[10] Siemens PLM Software. STAR-CCM+ User Guide (Version 12.04) 2017.

[11] Williams J. F, and Hawkings D.L. Sound generation by turbulence and surfaces in arbitrary motion. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 1969;264:321-342.

[12] Brentner K.S, Farassat F. Analytical comparison of the acoustic analogy and Kirchhoff formulation for moving surfaces. AIAAA J 1998;36:1379-86.

[13] Neise W. Review of fan noise generation mechanisms and control methods. In: Proceedings of the Fan Noise 1992 International Symposium, Senlis, France; 1992;45 56

[14] Johnson M. W, Moore J. The Development of wake flow in a Centrifugal Impeller, Journal of Engineering for Power. 1980;102:382-389.