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Aeroacoustic evaluation of the forward-curved fan inlet flow

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ABSTRACT

Forward-curved fans have been extensively used in various industrial and residential HVAC applications. Regarding their favourable characteristic properties, low noise emission and small size, forward-curved fans are used in various applications with requirement for high flow rates at moderate pressure and efficiency not being of primary importance. The shape of the fan's inlet channel is heavily influenced by limited space available, which results in adverse flow aerodynamics, affecting the efficiency. So far poor efficiency of the forward-curved fan was usually attributed to the flow separation in the interblade channel at the shroud side. Such vortical flow occupies about a third of the rotor's width, resulting in the interblade channel choking and thus efficiency reduction. This phenomenon was extensively researched by several authors, while the effects of inlet flow channel design on fan performance were rarely investigated.

In the course of this study an improved inlet channel was designed. The prototype's performance and noise characteristics were determined and furthermore, local measurements of flow velocity using hot wire anemometry were performed. A novelty approach with psychoacoustic metrics adopted to velocity signal processing was used to improve the understanding of aerodynamic phenomena in the inlet channel. The findings exhibit distinct regions of adverse vortical flow which correlate to the integral performance of the fan.

Keywords: Fan inlet channel, Aeracoustics, Local flow properties

1. INTRODUCTION

High rotor outlet to inlet ratio (about 3:1) and large number of short chorded blades (around 40) are the distinctive features of forward-curved (FC) fans. Despite their poor efficiencies, FC fans are commonly used in many domestic and industrial applications requiring high flow rates at moderate pressure increase, compact size, low noise emissions and low manufacturing costs. Wide area of application is probably the reason for vast research done on the topic of FC fans, most of which refers to phenomena close to the rotor. Only recently, a few studies refer to the lack of fan installation space and its accompanying phenomena, resulting in additional reduction of already low efficiency. None of those studies address the abrupt flow properties in the inlet channel, while most treat the inlet as open to the environment, also called free inlet configuration (not ducted).

In his book, Eck [1] dedicated a chapter to FC fans, noticing the flow separation zone at the inlet of the fan and proposing a few design guidelines, while pointing out the lack of fundamental knowledge for design and calculations. Since then, several research groups worked on the field of FC fans and published several papers on the topic. Flow field in the rotor was investigated by Kind [2,3], who pointed out the complexity of flow patterns with substantial axial and circumferential nonuniformity caused by separating inlet flow, especially at flow rates below the best efficiency point (BEP). Tsutomu [4,5,6,] published a three-part study on the blade shape design, flow around the runner blade and volute casing design. The study is based on numerical and experimental investigation of different rotors and volute casings, from which optimal number of blades, blade angles, volute size and magnifying/circumference angles were obtained. Later, a research group from Oviedo University in Spain studied [7,8,9] aerodynamic and acoustic properties of FC fans, especially the double inlet ones used for automotive HVAC systems. They performed a series of numerical and experimental

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studies, pointing out the effects of volute tongue design on the noise reduction and influence of operating point on highly nonuniform flow through the rotor. Simultaneously a research group from Amirkabir University of Technology, led by Montazerin also performed continuous research on the topic and based on their series of research papers in 2016 published a book [10] on developments in the field. The book covers all major aspects - inlet configuration, rotor and volute design, supported by experimental data acquired with laser doppler anemometer measurements and numerical modelling. Like Montazerin, Pham Ngoc Son [11] also investigated the effect of inlet geometry on the performance characteristics. The fans in the studies are all installed in the free inlet configuration, where inlet is opened to the environment and not ducted. The inlet design refers only to the inlet lips, as marked in the Figure 1. As shown in the results of the study, this relatively small portion of the inlet channel does not represent influential factor affecting fan characteristics. With respect to efficiency, Golamian [12] evaluates the effect of various flow straightener geometries, such as tubes and zig-zag plates at the inlet. The results show the negative effect on the pressure head and efficiency for any kind of straightener. With respect to lack of space, a study by Xuanfeng Wen et al. [13] addressed the effects of the discontinuous volute profile on the fan efficiency. Authors found, that such volute profile results in efficiency reduction and increased noise emission.

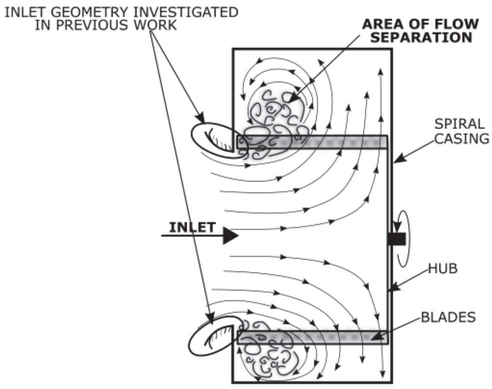

Figure 1 - Typical flow pattern through a forward-curved fan.

In conclusion, extensive work has been done on the topic since 1973, when Eck [1] pointed out the lack of research on the field. However, none of the research investigated the influence of ducted inlet configuration that commonly occurs with fans installed in various appliances. Moreover, the inlet channel is usually not straight but arranged at an angle to the axis of fan rotation, which in our experience results in additional efficiency reduction and increased noise emission. To evaluate its effects, we measured performance and noise characteristics of the fan in both free and ducted inlet configurations. Hot wire anemometry was used in the plane at the fan inlet to investigate the mechanisms causing the efficiency reduction.

Nowadays, psychoacoustic metrics became a frequently used tool for turbomachinery noise evaluation. However, we haven't found a single example of these metrics to be used with non-acoustic signal analysis. Pressure and velocity fluctuations are strongly related in fluid flows, which lays the ground of adopting psychoacoustic metrics to velocity signal analysis. With that in mind, loudness (DIN 45631/A1), sharpness (DIN 45692), fluctuation strength and roughness [14] were used as a tool to interpret the flow properties affecting the efficiency and noise level. Based on the results, a new prototype of the inlet channel, which increased the fan's efficiency and reduced its noise emissions was built.

2. MEASUREMENT APPARATUS

The experiments were performed on a measurement rig, built according to ISO 5801 – installation of category B (free inlet and ducted outlet). The rig is schematically shown on the Figure 2 and consists of a test section with the fan installed in a spiral casing (Figure 2-1). The spiral casing was constructed according to guidelines introduced by Montazerin [10]. The differential pressure transducer used to measure the pressure increase over the fan was connected to the tapping marked with A on Figure 2-1 with the other port open to the environment. A 60 mm wide runner with 40 blades and diameter of 155 mm was used. It was driven by a 400W servo motor that provides a constant rotational frequency of 50 Hz, independent of the load (operating point) and enables the measurement of the shaft torque. An orifice, installed according to ISO 5167 with flange tapings, was used to measure the flow rate (Figure 2-2) and an auxiliary fan and motorized throttle valve were used to provide a wide range of operating points (Figure 2-3). Noise characteristics were determined using a Norsonic Nor140 Sound Analyser, positioned 1 m away from the fan. The first part of the experiment consists of performance and noise characteristic measurement for each inlet configuration - free inlet, existing inlet channel (TD inlet) and the new inlet channel.

For the second part of the experiment a 3-axis traversing system was built for the identification of the deterministic flow patterns in the inlet channel using three motorized linear rails driven by stepper motors. A miniature 1D hot wire anemometer, Dantec type 55P11 was mounted on the system and positioned perpendicular to the flow direction in 144 measurement points as shown in the Figure 2 – right. A 10 s time series of velocity signal was acquired at each measurement point with the sampling frequency of 25 kHz, using NI9222 module mounted on NI9147 cDAQ chassis. The measurement and positioning process were fully automated and performed using a software built in NI Labview environment.

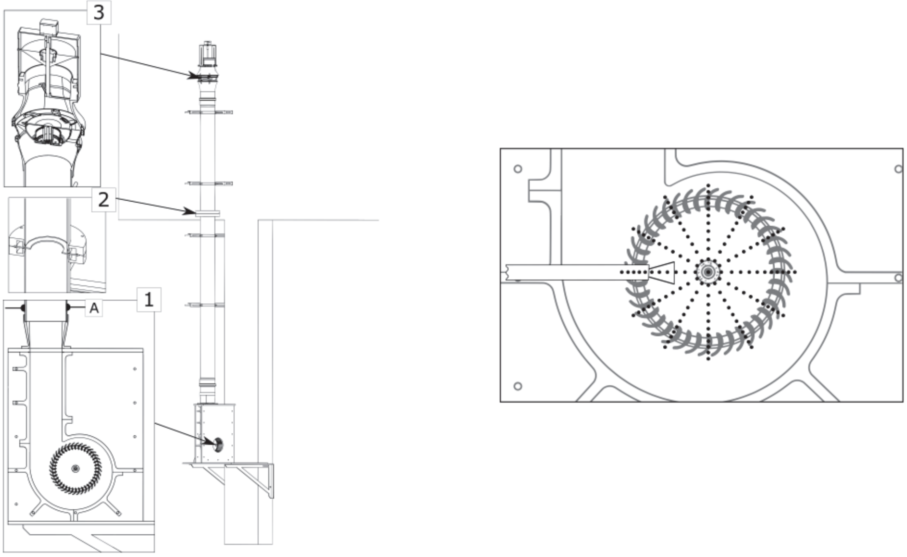

Figure 2 - Measurement rig, built according to ISO5801 (left) and schematic representation of the single wire anemometer setup with layout of the measurement points (right).

In addition to existing inlet (Figure 3, left), a new inlet was designed based on the interpretation of flow patterns in the inlet channel. During the iterative research process of channel shape effect on performance, various designs were investigated. Moreover, two basic approaches were investigated. First, we designed an inlet that mimics the free inlet configuration but realized that this approach results in lower efficiency when compared to the existing inlet channel. Secondly, we adopted an inlet that guides the streamline of the fluid to the inlet opening, resulting in higher efficiency and lower noise levels (Figure 3, right).

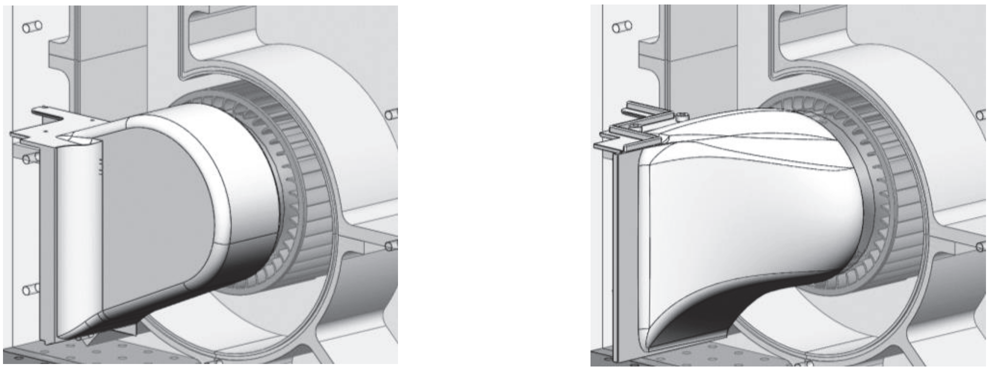

Figure 3 - Inlet channel development - existing design (left) and channel outline following streamlines (right).

3. RESULTS AND DISCOUSSION

Results show a comparison of free inlet, the existing inlet and the new inlet configurations. Integral aerodynamic and acoustic parameters - performance and noise characteristics are evaluated in the first part and local properties of the inlet flow are investigated in the second part.

3.1 Integral aerodynamic and acoustic properties

Performance characteristics of free inlet and both ducted inlet configurations are shown in Figure 4. All of them exhibit a distinct unstable area of operation up to about 200 m3/h. At higher flowrates the operation of the fan is stable for all inlet configurations. The phenomenon of partially filled interblade channels, causing the pressure increase in the case of FC fans with respect to fans with backward inclined blades for very low flow rates is well described by Eck [1 - p.114]. The stable part of the characteristics is well described with a fitted second order polynomial curve. Best efficiency point (BEP) occurs at 390 m^3/h for free inlet configuration, 300 m^3/h for existing and 340 m^3/h for new inlet channel. Hydraulic efficiency at BEP is estimated to 50 % for free inlet configuration, 37,5 % for existing and 41,5 % for the new inlet channel.

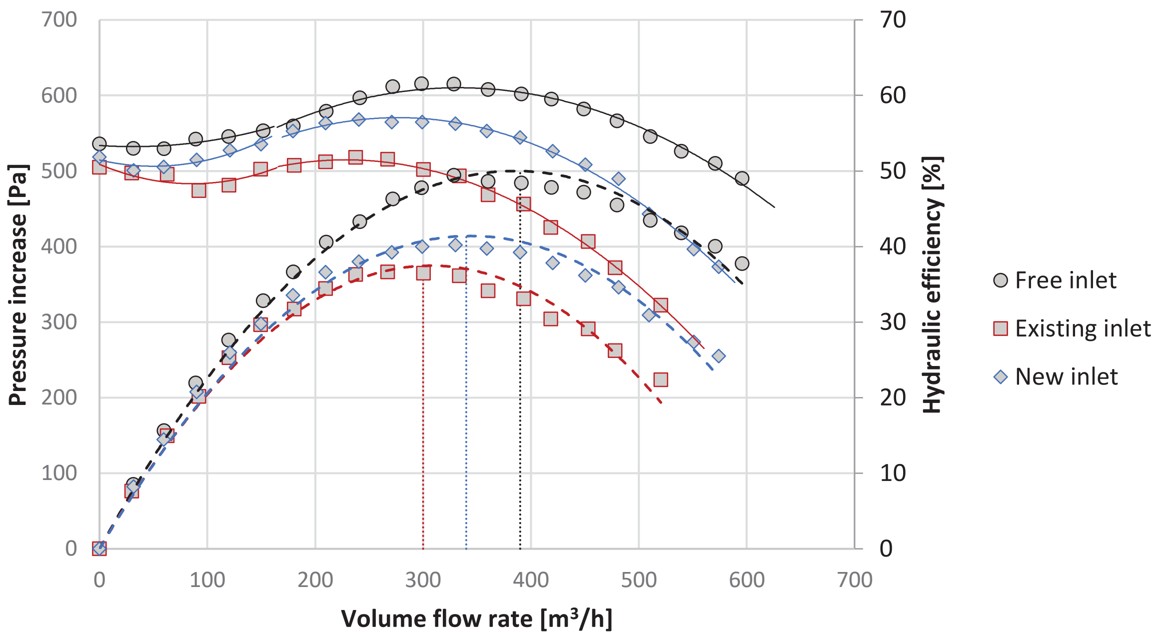

Figure 4 - Performance and efficiency characteristics of the fan in free inlet configuration (black), with existing (red) and new inlet (right).

Noise characteristics (Figure 5) with all inlet configurations exhibit lower noise levels at lower flow rates, while the lowest values don't coincide with BEP as proposed by the fan noise theory. In the case of free inlet, the Leq(A) levels are generally higher with respect to the two ducted configurations, which is a consequence of the inlet channel acting as a noise shield. Therefore, these cases should not be directly compared. The comparison of the existing and new inlet channel exhibits a 2 dB(A) noise reduction at higher flow rates in the case of new inlet configuration, while the difference below 250 m^3/h is negligible. The difference is attributed to the reduction of aerodynamic noise, since everything, but inlet channel geometry remained identical. In the case of the new inlet channel, noise reduction and thus efficiency increase is attributed to vorticity reduction and improved flow conditions in the inlet channel.

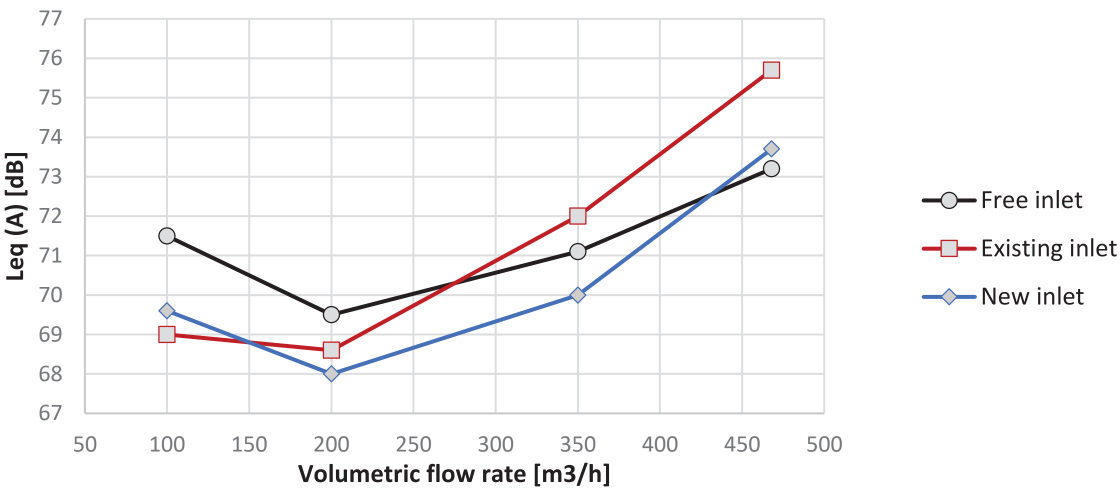

Figure 5 - Noise characteristics of the fan in free inlet configuration (black), with existing (red) and new inlet (right).

The maximum efficiency limit, proposed by the free inlet configuration is still about 10 % higher, but an important step forward was made with the new inlet channel design. An investigation on mechanisms causing the efficiency increase was performed, results of which are presented in the next subsection.

3.2 Local flow properties at the inlet plane

Local flow patterns at the fan inlet were recognized using smoke visualization technique coupled with laser sheet illumination and later with hot wire anemometry. Based on the visualization results, three distinct regions were identified: well filled region with negligible vorticity (Figure 6 - A), turbulent eddy region with little throughflow (Figure 6 - B) and a region in between with a distinct continuous vortex (Figure 6 - C). Vortex C is assumed to be driven by the previous two, while regions A and B are set to the nature of the rotor and spiral casing. The photo in the Figure 6 – left was captured with existing inlet at 200 m^3/h. The limitations of smoke visualization technique – dilution of smoke at high flow rates and view obstructed by the channel walls, make comparison of phenomena with respect to flow rate or inlet channel variation inconvenient. Hence the results of hot wire anemometry were used.

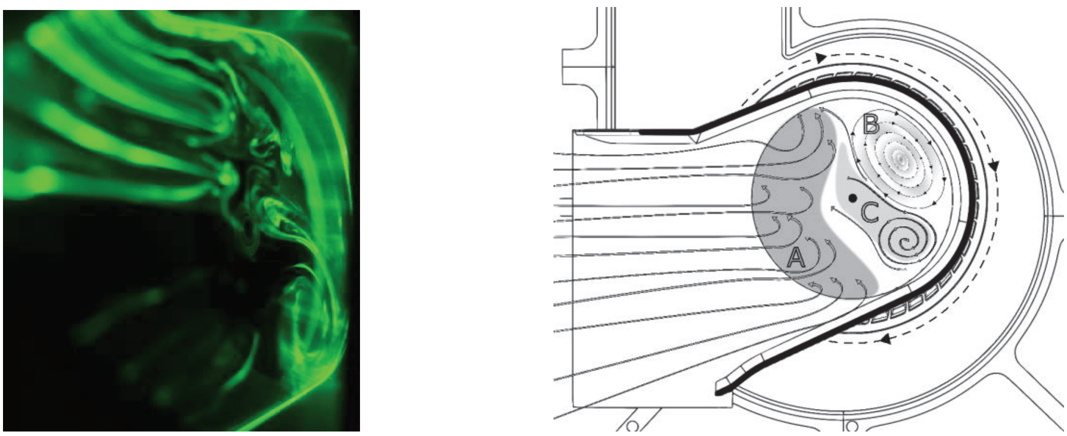

Figure 6 - Visualization of the flow field in the existing inlet channel at 200 m^3/h (left) and a scheme of flow field as interpreted based on the visualization (right).

To describe flow dynamics in regions A, B and C, psychoacoustic metrics adopted to velocity fluctuation signal were used. Average values of velocity magnitude, turbulence intensity and four psychoacoustic metrics - loudness, sharpness, fluctuation strength and roughness are shown as a function of flow rate in Figure 7. Results are shown as contour graphs (with equal scale range except for velocity distribution) of each variable distribution over the inlet area. The region marked with red colour represents the existing inlet while the new inlet channel is marked blue.

Based on the velocity distribution, two distinct regions can be recognised – a region of high velocity at the left half of the inlet opening and a region of low velocity on the right, behind the volute tongue. This corresponds to the previous conclusion, based on the results of visualization. The high velocity region corresponds to the well filled region with negligible vorticity, while the low velocity region corresponds to the turbulent eddy region with little throughflow. The latter is also a region of high turbulent intensity, which corresponds to the previous assumption. In this manner loudness was found to provide additional insight on the fluctuation properties in the turbulent region, representing the level of velocity fluctuation. We can observe a slight reduction of loudness and sharpness in the area marked with A in the Figure 7, which is attributed to the contraction of the new channel at that exact place (Figure 3). It seems that the contraction guides the flow in a positive manner, reducing the vorticity in the turbulent eddy region (Figure 6 - B).

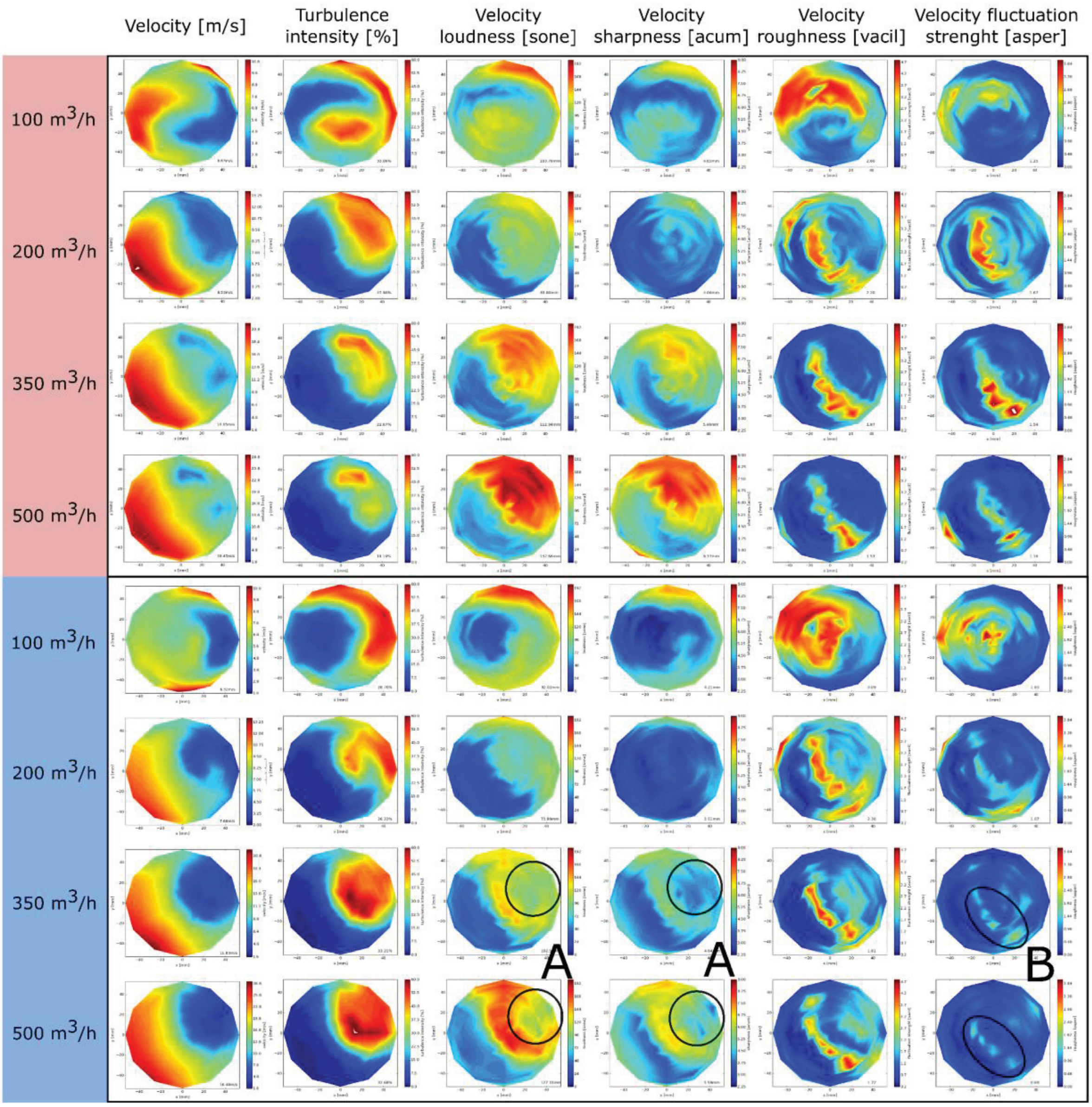

Figure 7 - Local flow properties in the plane at the inlet of the fan for existing (red) and new inlet channel (blue) with respect to the volumetric flow rate.

While loudness does not contain the information about the frequency band of fluctuation, sharpness, roughness and fluctuation strength were added. Sharpness is a hiss like property of sound, dominated by energy at high frequencies. Increased levels of sharpness and thus dominant high frequency fluctuation typically occur in the turbulent eddy region, which shows similar spatial distribution to loudness. Therefore, a conclusion can be drawn that all turbulent regions contain high frequency fluctuations.

The region between the well filled region and the turbulent eddy region, where a distinct continuous vortex occurs (Figure 6 - C) is indicated by elevated values of all psychoacoustic metrics, indicating broadband characteristic of fluctuation. This is the only region with elevated roughness and fluctuation strength, while the flow dynamics in rest of the inlet region is characterised by either high or low frequency. Roughness and fluctuation strength exhibit similar behaviour, indicating loudness modulation at frequencies under and over 30 Hz, respectively. In relation to aerodynamic phenomena, we attribute the region of increased fluctuation strength and roughness to the presence of large vortices. Large scale vorticity occurs due to high velocity gradient in the transitional area between well filled region with negligible vorticity (Figure 6 - A) and the turbulent eddy region (Figure 6 - B). At 350 and 500 m^3/h a slight reduction of fluctuation strength was observed with new inlet (Figure 7 - B), which could cause previously indicated efficiency increase and noise reduction.

Elevated values of roughness and fluctuation strength occur at 100 m^3/h in the otherwise well filled region with negligible vorticity – left half of the inlet opening. The latter indicates presence of large scale vorticity, representative of low flow rates, choking the inlet channel and thus affecting the efficiency.

Overall, low values of all psychoacoustic metrics occur at 200 m^3/h, which is the flow rate with the lowest noise level. This phenomenon indicates the relation between the fluctuation intensity and the emitted noise. With respect to volume flow rate, a significant distribution alteration of all metrics was found at 100, 200 and 350 m^3/h, while results at 350 and 500 m^3/h don't exhibit such alterations.

CONCLUSION

Forward curved fans are used in a wide variety of industrial and domestic applications and thus the well-studied in the past, while the problem of efficiency reduction due to abrupt flow conditions in the inlet channel was however not investigated. Our study was focused on the effect of the inlet channel geometry on the integral aeroacoustic properties of the fan and the determination of local flow properties, which were used to interpret variations among integral characteristics. The existing inlet channel was improved with a new one, resulting in a 4 % efficiency increase and 2 dB(A) noise reduction. Visualization with smoke and laser sheet illumination was performed, identifying three distinct flow regions: well filled region with negligible vorticity, turbulent eddy region with little throughflow and a region in between featuring a continuous vortex. Furthermore, traversing with a hot wire anemometer on the inlet plane was performed and velocity fluctuation signal processed in a manner to explain the flow patterns with respect to channel geometry and flow rate. A novel method of psychoacoustic metrics was adopted to velocity fluctuation signal. The method was found useful for flow pattern interpretation, indicating dominant fluctuation frequency band with respect to position in the inlet plane. The new inlet exhibits a reduction of high frequency fluctuation in the turbulent eddy area (Figure 7 - A) and vortex reduction (Figure 7 – B), causing the 4 % efficiency increase and 2 dB(A) noise reduction.

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