AEROACOUSTICAL INVESTIGATIONS ON AXIAL FANS FOR AUTOMOTIVE COOLING SYSTEMS

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SUMMARY

The scope of this project is to investigate the influence of skewed blades to the aerodynamic and acoustic behaviour of axial fans. Therefore axial fans with different skewed geometries were built and measured. The variations include unskewed, backward and forward skewed blades. The strength of the skew is also varied and includes different forms for forward skewed axial fans. To explain the lower efficiency in the case of the forward skewed axial fan and the best result in the noise propagation, numerical investigations were carried out.

INTRODUCTION

The aerodynamic noise generated by axial fans is usually an addition of tonal and broadband components. The noise in axial fans at lower Mach numbers is mainly attributed to the blade forces. These forces can be separated into steady and unsteady forces, the first ones resulting from the function of the fan and can not be avoided (so-called Gutin noise). The unsteady blade forces generate the largest part of the total noise [1, 2]. Possible mechanisms for these are: Interaction of turbulent inflow to the fan with the rotating blades, the flow separation at the fan blades, the interaction of the turbulent boundary layer with the blade trailing edge and the gap flow.

A widely used technique to reduce noise from axial fans in disturbed environment, like the case in the car installation situation, is to skew the axial fan. Former investigations about the influence of the skew to the aerodynamic and therefore the acoustic behaviour are not entirely clear. They are examined in this work in more detail. The main focus of this work is the investigation of the influence of different skewed axial fans on the acoustic behaviour, while keeping the aerodynamic load constant.

CONFIGURATION AND FAN GEOMETRY

The studies are performed at the Institute of Fluid Machinery (FSM) of the Karlsruhe Institute of Technology (KIT).

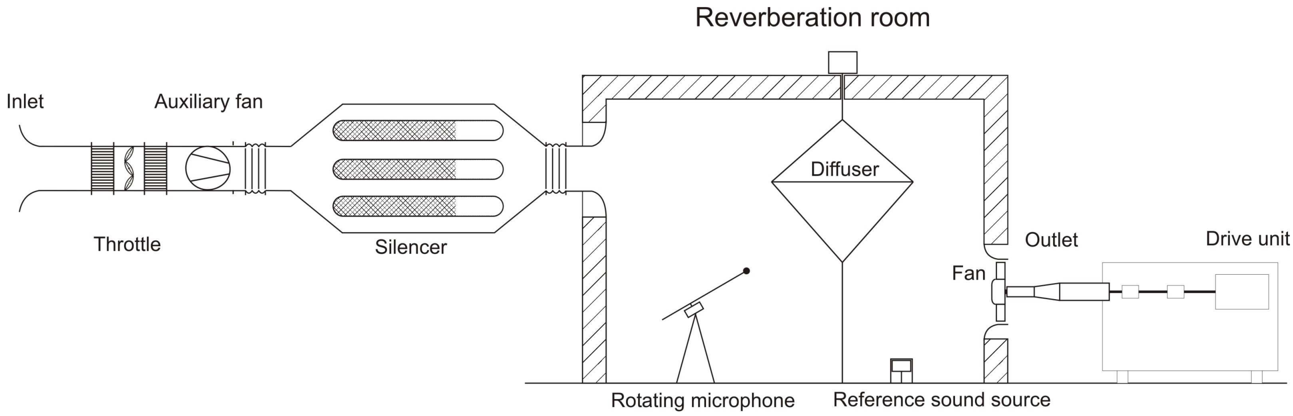

Figure 1: Aero-Acoustic test rig

This test rig allows simultaneous measurements of the aerodynamic (ISO 5801) and acoustic (ISO 3741) parameters (see Figure 1).

The fan is installed at the outlet of the test rig and blows the air from the reverberation room out in the laboratory hall. The characteristic parameters are: Volume rate (at the inlet-nozzle via differential-pressure principle), pressure increase, rotational speed and torque at the drive unit and even the sound pressure fluctuation are measured simultaneously. For the measurement of sound pressure fluctuation a rotating microphone is used. An unsymmetrical diffuser rotates in the middle of the room to homogenize the diffuse field. In the reverberation room a reference sound source is installed to calculate the sound power level by using the comparative method.

The instrumentation for noise measurement consisted of a Brüel & Kjaer diffuse-field microphone of 1/2" diameter type 4943, digital 2-Channel Front End (BEQII). Recording and analyzing was done by the software Head Recorder and Artemis from HEADacoustics®.

The used axial fans for this purpose have mostly a ring at the blade tips and so a special gap shape. The selected shape is similar to a labyrinth seal and should minimize the gap flow and thus the leakage losses (see Figure 2).

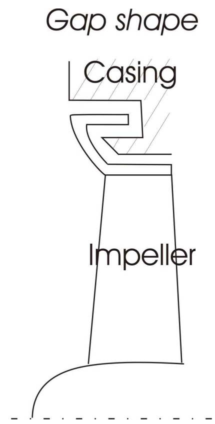

Figure 2: Gap shape (meridian cut)

General geometric dimensions and operating conditions are shown in Table 1.

Table 1: General Dimensions of the fans

Hub-tip ratio	υ	-	0.42
Solidity at D_a	l/t	-	0.476
Gap ratio	$2*s/D_a$	-	0.017
Rotational speed	n	rev/min	3000

The study includes a variation of the skew at a fan with 7 blades. One backward and three forward skewed fans were built. The forward skew includes three stages, one weak skewed fan (FSK_W, Figure 3: c), one middle skewed fan (FSK_M, Figure 3: b) and one strong skewed fan (FSK_S, Figure 3: a). The backward skewed fan is weak skewed and so called: BSK_W (Figure 3: e). To complete the naming the unskewed fan is called: USK (Figure 3: d).

a b c d e

Figure 3: Forward skewed, unskewed and backward skewed axial fans

The stage of the skew is related to the spacing of the outer profile (weak: 30%, middle strong: 45% and strong: 60% of the blade spacing at the outer diameter). All of these fans have similar blade shape based on NACA 65-series and has been designed as an evolution of the original USK concept. The vortex design of all the fans is identical and is reduced at the hub and at the tip. The axial velocity at the inlet of the fan is assumed to be constant.

To reach the aim of constant loading by changing the blade skew corrections are required. The design of the skewed fans was realized under consideration of the corrections for Beiler [3, 4] and blade adjustment.

The characteristic curves are given by dimensionless ratios. The volume flow coefficient (based on the area the flow passes through), the pressure coefficient (system: blowing out pressure difference), the efficiency (system) and the circumferential speed at the outer diameter are defined as follows:

$$\varphi_{LA} = \frac{Q}{\left[\frac{\pi}{4} D_a^2 \left(1 - \upsilon^2\right) u\right]} \quad (1)$$

$$\psi_{fa} = \frac{\Delta p_{fa}}{\left(\frac{\rho}{2} u^2\right)} \quad (2)$$

$$\eta_{fa} = \frac{Q\, \Delta p_{fa}}{P_W} \quad (3)$$

$$u = \pi n D_a \quad (4)$$

EXPERIMENTAL INVESTIGATIONS - RESULTS

The configuration for the measurement was without any component neither in the upstream nor the downstream flow, so free in- and outflow.

Figure 4 shows the characteristic curves of all studied fans. The comparison of the different characteristic curves shows very small difference especially in the range of best point (φ≈0.14) and when considering a given system curve.

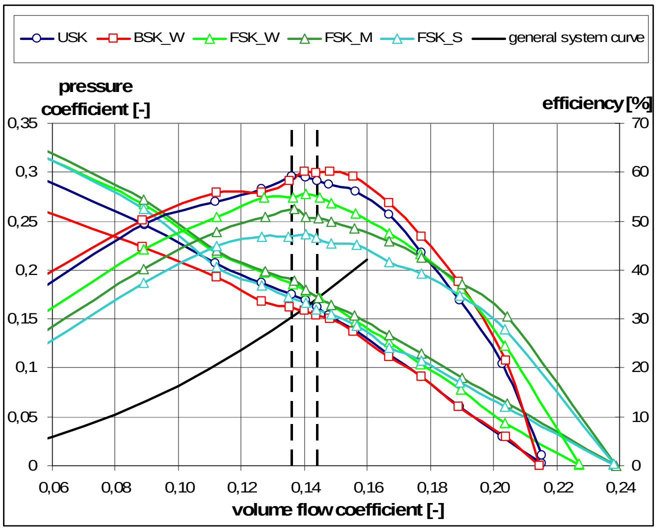

Figure 4: Characteristic curves

The following remarks about the consideration of the characteristic curves are carried out from the higher to the lower volume flow coefficient. The characteristic curve of the backward skewed fan starts, with decreasing volume flow rate, to become instable at φ≈0.15 and deviate from the curve of the unskewed fan. Nevertheless the curve of the backward skewed fan is in the range of best point almost identical with the unskewed fan. The curves of the forward skewed fans are almost identical and very close to the characteristic curve of the unskewed fan. The curves of the forward skewed fans are characterized by the fact that they hardly show instable range even in the partial load (this fits with [5]). Hereby the goal of this study, to skew fans by retention of the similar loading, was reached. The comparison of the efficiency shows an increase of the efficiency (1-2 %) by the backward skewed fan in comparison to the unskewed fan and the small displacement of the best point to higher volume flow coefficient (φ≈0.15). In the case of forward skewed fans the efficiency becomes, depending on the strength of the skew, more and more lower and move to lower volume flow coefficient (φ≈0.13). The decrease of the efficiency is of 3 % by the weak skewed fan, 7 % by the middle strong skewed fan and 12 % in case of the strongest skewed axial fan. This reduction of the efficiency is also due to the increase of the shaft power as in Figure 5 presented.

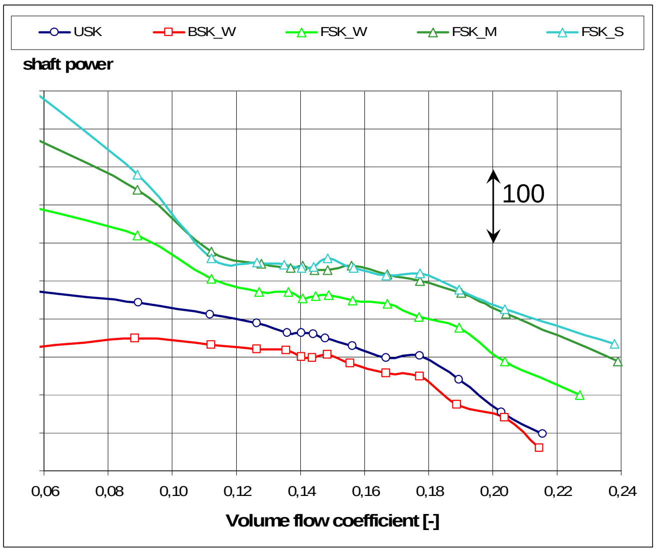

Figure 5: Shaft power curves

The deterioration of the efficiency at the case with forward skewed fans was mentioned in previous works [6]. In Figure 6 the acoustic curves of all axial fans in this study are presented. In the range of best point the sound pressure level of FSK_W is almost identical to the unskewed USK. The FSK_M and the BSK_W are about 1.5 dB less than the unskewed axial fan. The best result was reached by the FSK_S where the sound pressure level is almost 5 dB less than that of unskewed fan USK.

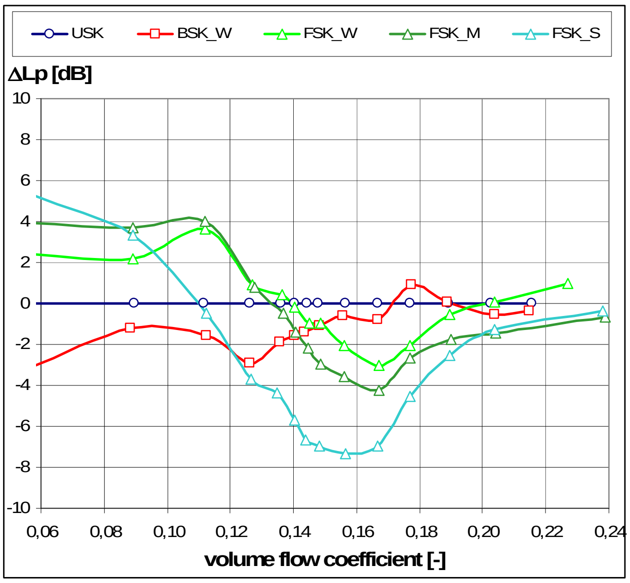

Figure 6: Sound pressure level

In Figure 7 the frequency spectra of all the axial fans from this study are presented. These consist of broadband, tonal components but also narrow-band enhancement next to the blade passing frequency (BPF) and its harmonics. A previous study [9] demonstrated that by avoiding the gap flow this narrow-band enhancement decrease immensely.

The main difference between the different axial fans is located in the range of 250 Hz to 4000 Hz so broadband noise in medium frequencies. A really important part here is the sharp decline of the narrow-band enhancement next to the BPF (about 300 Hz and its harmonics) for the case of strong skewed fan. This disappears completely around the frequencies 550 Hz, 850 Hz and 1150 Hz. Possible explanation for this purpose is the limitation of the leakage losses due to the forward skew [5] and the diminution of the noise propagation due to the interaction of the gap flow with the fan.

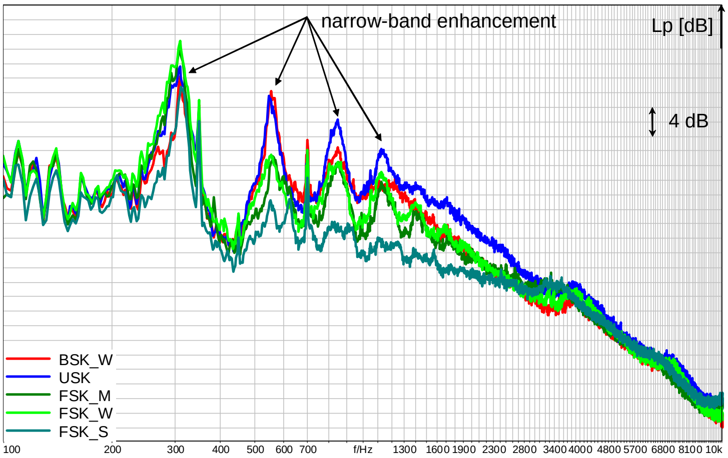

Figure 7: Frequency spectra at φ≈0.14, Δf=2.7 Hz

Figure 8 shows the comparison of the tonal components at the first and second blade passing frequency of all axial fans. The absolute value at BPF (see Figure 8 left) in the case of the FSK_W is the highest and the FSK_S the lowest, but the difference between both values is not more than 3 dB. If the difference between the maximum level and the corresponding basic level (enhancement of the tonal component) would be considered then the forward skewed fans show slightly higher values (2-4 dB). Figure 8 (right) shows differences in the absolute values at the second BPF between BSK_W and FSK_S (6 dB), but if the difference of the enhancement of the tonal component is considered there would be a negligible difference between the values of all variants.

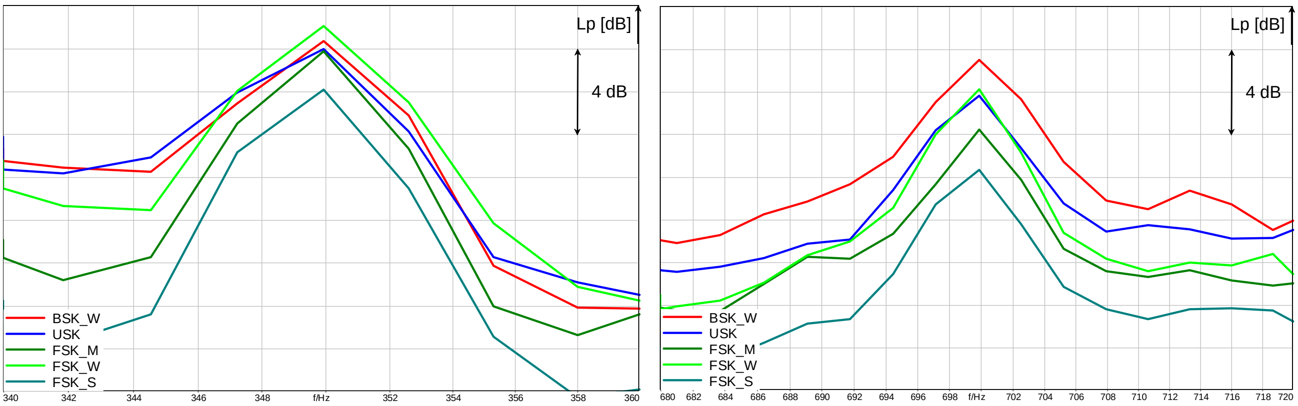

Figure 8: BPF (left) and second BPF (right) at φ≈ 0.14, Δf = 2.7 Hz

The comparison of the frequency spectra of the A-weightened noise of the axial fans (Figure 9) shows more clearly the difference between the unskewed and skewed fans. Even the FSK_W is equal with the BSK_W (both weak skewed) but now 3 dB(A) less than the unskewed fan. The improvement in the case of FSK_S is in the range of 7 dB(A) in comparison to USK. Here it can be concluded that the skew of axial fans has an influence on the frequency distribution of the noise propagation.

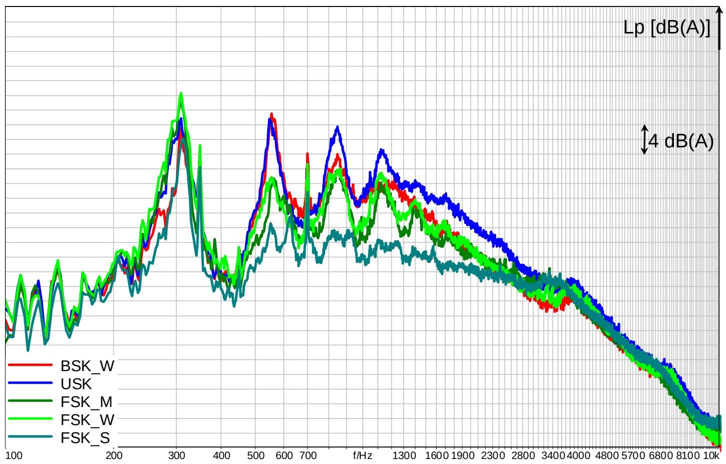

Figure 9: A-weightened frequency spectra at φ≈0.14, Δf=2.7 Hz

NUMERICAL INVESTIGATIONS - PROCEDURE

For the computational analysis the commercial code ANSYS®-CFX 12.1 was used. Because of the low Mach number the fluid can be considered as incompressible. Turbulence is modeled by the k-ω-SST model which has proven its reliability for adverse pressure gradient aerodynamic flows [7, 8]. The geometry is discretised by a 3-D-blockstructered mesh of about 600000 cells. The geometry and mesh generation was built with an in-house code which was developed at our institute. Wall function approach is used near the walls. The advantage of the wall function approach is that the high gradient shear layers near the wall can be modeled with relatively coarse meshes. All calculations presented in this work have mean y+ values between 30 and 120. The whole domain was divided into a rotor- and stator-domain. The rotor-domain includes the blade, hub and the ring and is defined as a rotating domain with fixed grid, whereas the rest of the fluid-domain is defined stationary as the stator-domain (see Figure 10). The interface between the rotor and the stator is defined as a frozen-rotor-interface. The specified boundary conditions in this problem are shown in Figure 10 and consist of a constant mass flow rate at the inlet and a constant static pressure of 0 Pa at the outlet. Reference pressure is 1 atm.

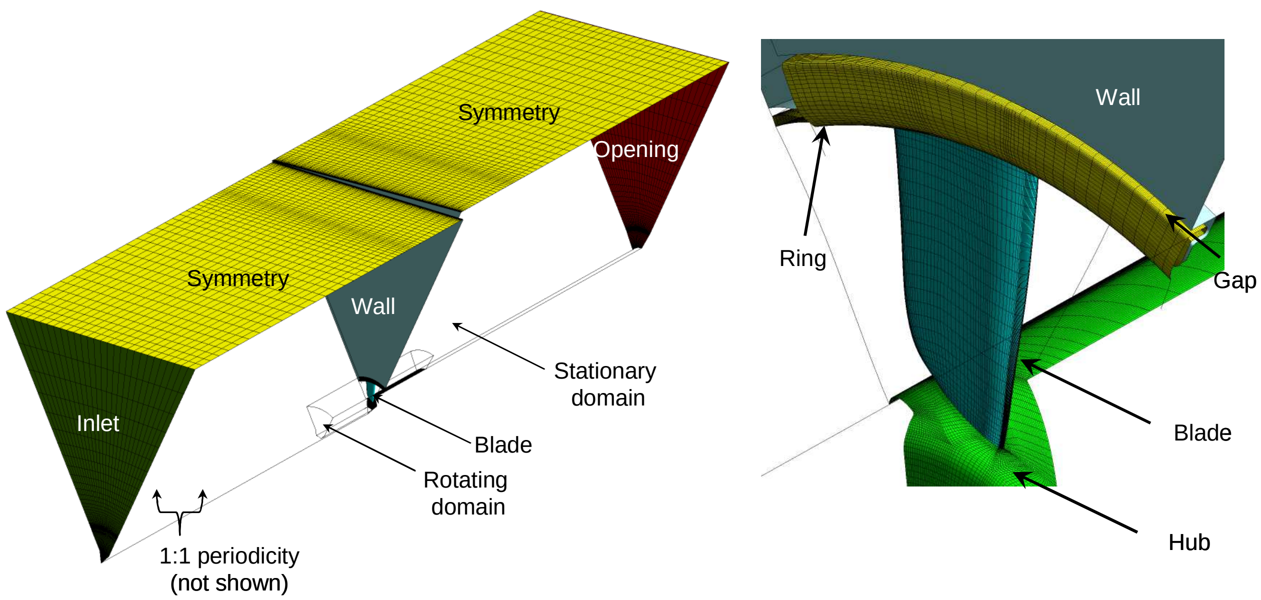

Figure 10: Fluid-domain and boundary conditions used

NUMERICAL INVESTIGATIONS - RESULTS

Figure 11 shows the characteristic curves of the experimental measurement compared to the results of the numerical investigations. It is visible that the agreement between the experimental and the numerical results is very satisfying. Especially the trends between the unskewed and the different skewed axial fans are very well reproduced.

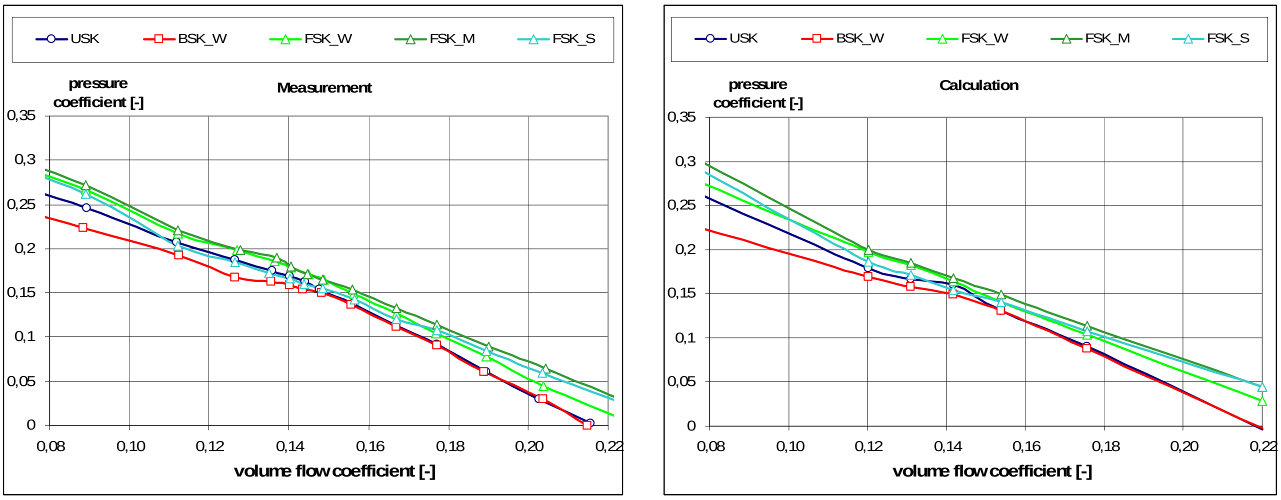

Figure 11: Comparison of the experimental (left) and numerical (right) pressure coefficient curves

The analysis of the numerical investigations includes the variants BSK_W, USK and FSK_S (representing the three forward skewed variants). The comparison of the surface streamlines for the suction side of the blade in Figure 12 and the pressure side of the blade in Figure 13 deliver more information about the flow through the axial fans. It is obvious that the forward skew forces the flow to go towards to the hub which leads to the stabilisation of the hub flow and the avoidance of the hub separation. This can be observed in Figure 13 more clearly where the hub separation for FSK_S is much less than for BSK_W. For this reason the characteristic curve of BSK_W shows an instable region at φ≈0.15 and deviate, with decreasing volume flow rate, from the curve of USK. The curves for the forward skewed fans (FSK_W, FSK_M and FSK_S) show a very stable curve even at the partial load (lower volume flow rate).

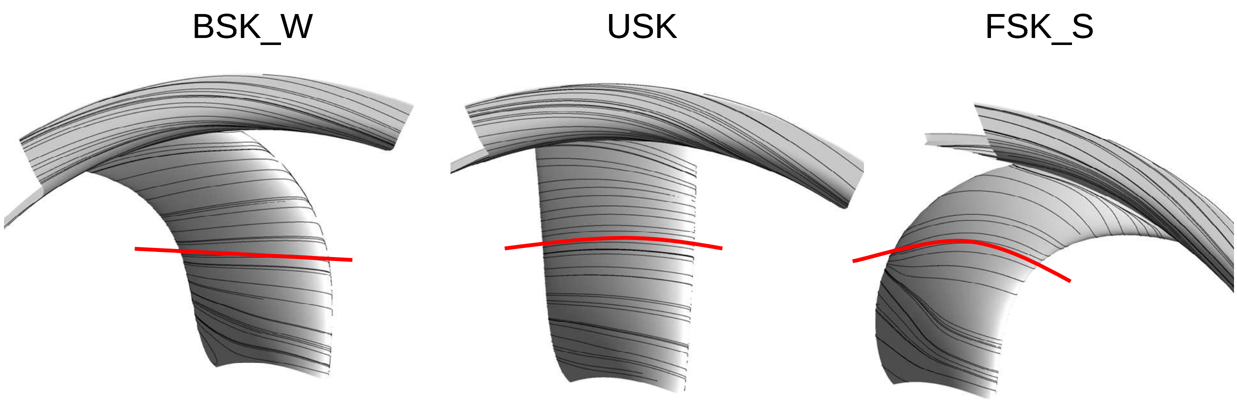

Figure 12: Surface streamline at blade and ring (front view)

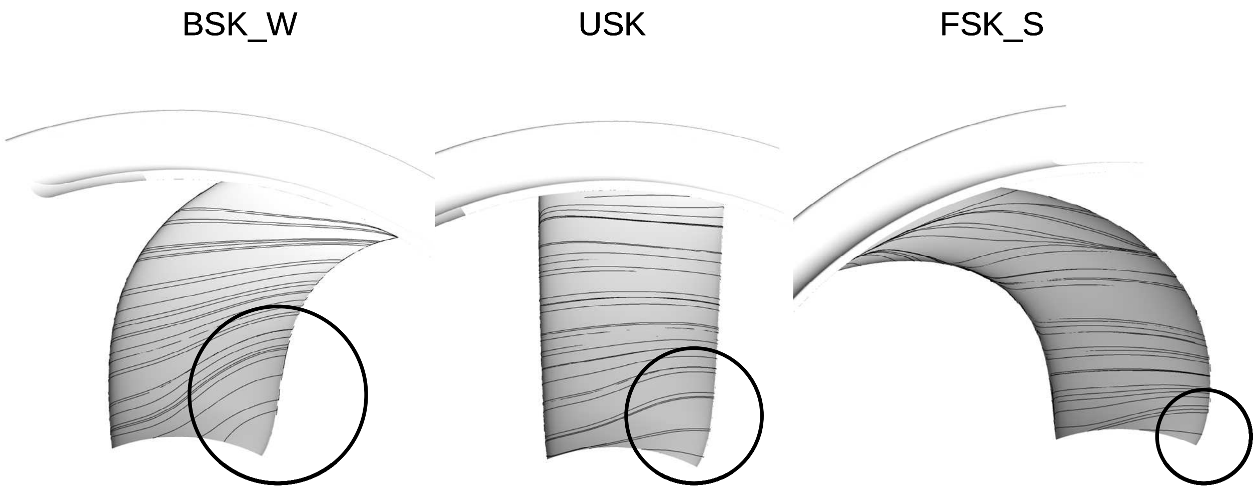

Figure 13: Surface streamline at blade and ring (rear view)

The comparison of the efficiency curves is presented in Figure 14. Also these curves show a good accordance between the experimental measurement and the numerical investigations.

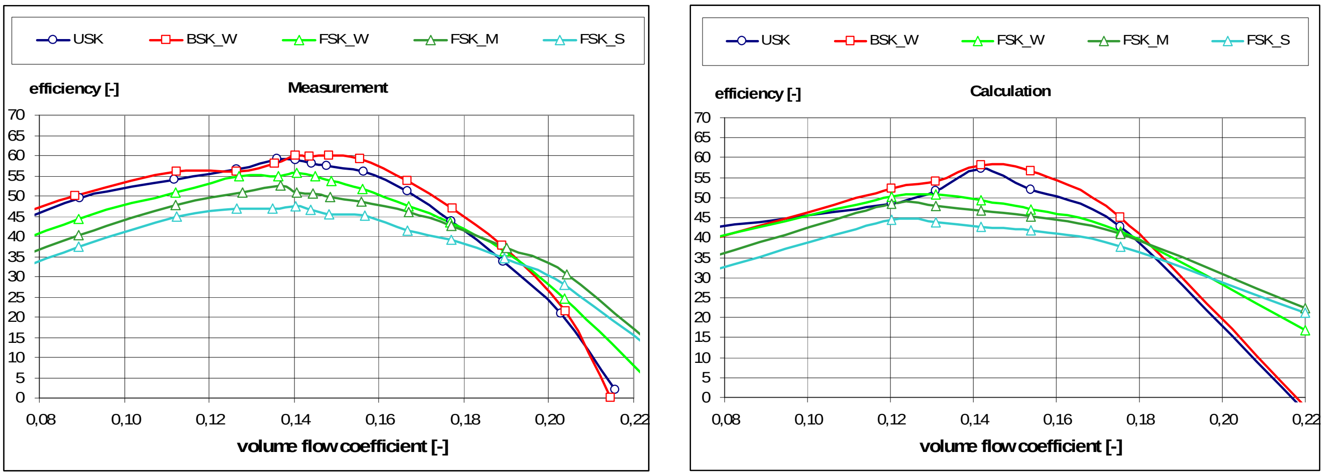

Figure 14: Comparison of the experimental (left) and numerical (right) efficiency curves

The analysis of the streamlines in a turbo surface at 96% of the outer diameter is shown in Figure 15. The analysis of these streamlines shows an amelioration of the flow situation around the blade in this blade section for the case BSK_W in comparison to the unskewed axial fan. In contrast to that is the analysis of the streamlines for the variant FSK_S, which shows the deterioration of the inflow to the blade and therefore the increase of the shock losses in this case. This comparison can be the explanation for the decrease of the efficiency curve for the case of FSK_S (about 12% in the experiment) in comparison to USK. With the amelioration of the inflow to the blade for BSK_W the shock losses can be diminished which explain the amelioration of the efficiency here (1-2% in the experiment).

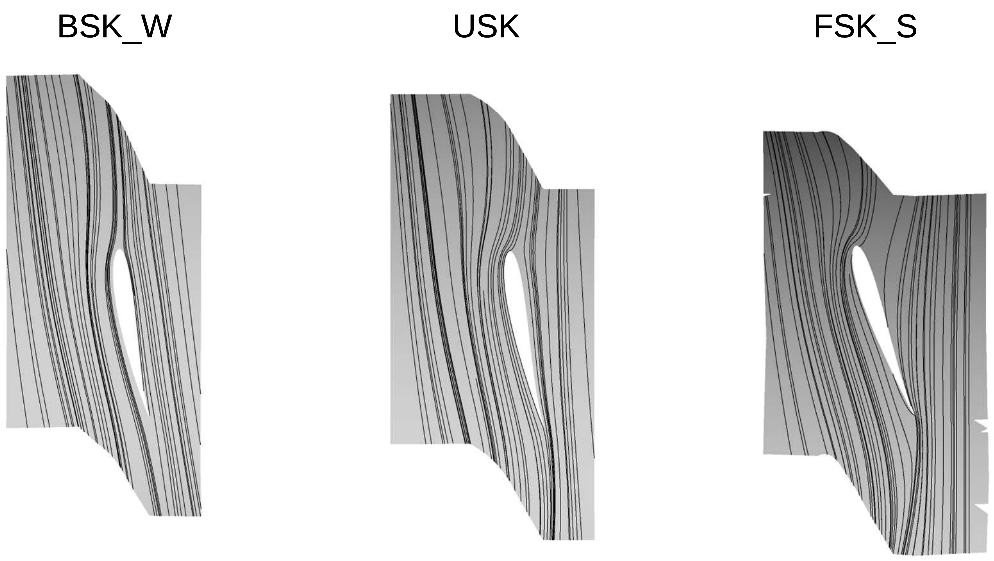

Figure 15: streamlines around the blade at the outer region (blade section at 96% of the outer diameter)

Figure 16 describes the difference in the velocity in stationary frame in the gap region between the three types of blade: BSK_W, USK and FSK_S. As it was mentioned in the previous section of this work that the skew has an influence of the flow through the fan (forward skewed fan force the flow towards the hub and the backward skewed fan force the flow towards the casing) this would affect the gap flow and hence the leakage phenomena as well [5]. The velocity magnitude of the flow from the gap diminishes in the case of FSK_S (see Figure 16) and the amplitude of the recirculation region from the gap decrease in comparison to the BSK_W and USK. This could be the reason for the diminution of the interaction of the rotating blade with the gap flow and also the noise emission generated from this mechanism.

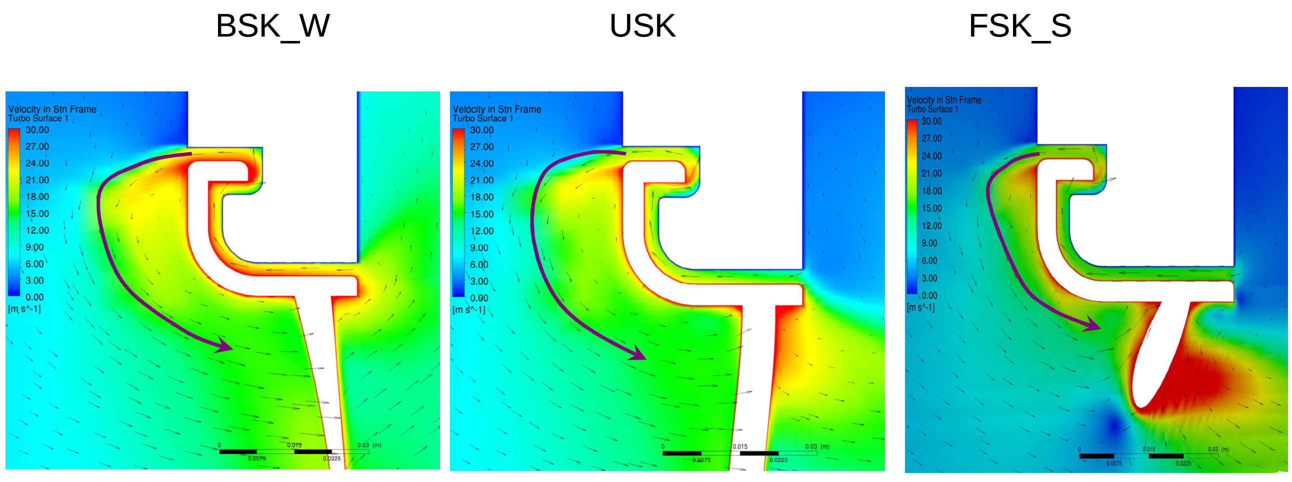

Figure 16: Gap flow comparison between BSK_W, USK and FSK_S

CONCLUSION AND OUTLOOK

The skew of the blades plays an important role on the aerodynamic as well as on the acoustic. The comparison of the efficiency shows an increase by the backward skewed fan in comparison to the unskewed fan and the small displacement of the best point to higher volume flow coefficient. In the case of forward skewed fans the efficiency decreases and moves to smaller volume flow. The amount of decrease depends on the strength of the skew and is respectively 3%, 7% and 12% for the strongest forward skewed axial fan. The comparison of the acoustic graphs shows the best result with the strong forward skewed axial fan and is about 5 dB less than the unskewed fan. This difference relates to the broadband noise and is mainly in the range between 400 Hz and 4000 Hz. An important advantage by the strong skewed fan is the decline of the narrow-band enhancement next to the blade passing frequency. The gap flow for the variant FSK_S decreases also and could be the reason for that. This phenomenon in the spectra disappears completely by the strongest forward skewed fan. In this investigation and for the configuration free in- and outflow the skew of blades doesn't have big influence on the tonal component of the noise propagation.

To find out the reasons for these observations more information about the influence of skewed blades on the gap flow and the related narrow-band enhancement or the main flow and the related broadband noise are planned and have to be compared with the assumptions made.

The skew of the near hub part of the blade was maintained constant (unskewed) for all the axial fans studied in this project. This would be modified in future work where a combination of backward skew in the outer part of the blade is mixed with a forward skew of the near hub part of the blade by maintaining the loading constant and measuring the acoustic and the aerodynamic. Aim of this future work is more details of the influence of the hub flow on the acoustic of the axial fans.

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