BROADBAND NOISE SOURCE MODEL ACOUSTICAL INVESTIGATION ON UNSKEWED AND SKEWED AXIAL FLOW FAN ROTOR CASCADES

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ABSTRACT

The aim of this investigation is the acoustical comparison of the broadband noise sources for two fans, the one being the datum unskewed case and the other a circumferentially forward skewed case, using computational fluid dynamics and broadband noise source models. In this way the acoustical advantages of forward skewed blades can be investigated while also providing a means for developing a methodology for use in research and industry, which allows the quick and cost effective comparison of different fans. Results verified the favourable behaviour of the skewed blade with respect to the tip leakage vortex. The less significant broadband noise sources, which are unsteady surface blade pressure, trailing edge noise and passage vortex interaction with the suction side stall, showed that the forward skewed blade investigated here needs geometrical corrections in order to fix the angle of attack and make the forward skewed blade the acoustically favourable of the two designs. The use of broadband noise source models for comparing fan designs is found to be an effective methodology for identifying all the broadband noise sources found in the literature.

Keywords: **aeroacoustics, broadband noise source, circumferential forward skew, CFD, turbomachinery**

NOMENCLATURE

A_c	$[m^2]$	Correlation area
$I(\vec{y})$	$[W/m^2]$	Sound intensity
P_A	$[W/m^3]$	Acoustic power
$S(\vec{y})$	$[m^2]$	Integration surface
a_0	$[m/s]$	Speed of sound
k	$[m^2/s^2]$	Turbulent kinetic energy
p	$[Pa]$	Pressure
t	$[s]$	Time
α_ε	$[-]$	Rescaled constant
ε	$[m^2/s^3]$	Dissipation rate
ρ_0	$[kg/m^3]$	Ambient density
$-$	$[-]$	Mean

1. INTRODUCTION

This paper presents a computational case study on the acoustical effects of Circumferential Forward Skew (FSK) for two comparative rotors. FSK is a non-radial blade stacking technique by which the sections of an unskewed (USK) straight datum rotor blade are swept forward and given dihedral in the direction of rotation [1, 2]. FSK offers a potential for the improvement of aerodynamic performance and total efficiency [2, 3] as well as simultaneously providing a means for rotor noise reduction if the blade skew is properly accounted for in the design phase [1].

In the literature, it can be found that, for axial flow turbomachinery, investigations of the effect of sweep on noise generation and propagation have been investigated in [4-7], but few were found which focused on the acoustic characteristics of turbomachinery with skew, especially with regard to FSK [1, 8-10]. In the literature, it was also found that most investigations focus on the tonal components of axial flow turbomachinery noise, utilizing unsteady investigations [6, 9 and 11], and only a few focus on examining the Broadband Noise Sources (BNS) [5, 10 and 12], which are becoming more and more of an issue with the reduction of the tonal noise components [5].

This study aims at filling this gap in the literature, by providing a comparative study between an USK and a FSK rotor using BNS models. Two of the BNS models available in the commercially available finite-volume Computational Fluid Dynamics (CFD) code FLUENT 6.3.26 were utilized. These are the Proudman's Formula Model and The Boundary Layer Noise Source Model [13]. This was done in order to demonstrate the impact of FSK on rotor aerodynamics and noise, thus contributing to a more comprehensive understanding of noise generation

mechanisms. The methodology applied in this investigation is also important, since the authors hope to provide a cost effective acoustic design and evaluation methodology for designers and researchers, since it can be seen in the industry that the need for such a fast and cost effective comparison methodology for turbomachinery acoustics, using only steady-state CFD results, is needed [7], yet no such methodology has been found in the literature which provides a comprehensive and cost effective method using the BNS models.

2. TURBOMACHINERY NOISE SOURCES

The sources of turbomachinery noise, which are focused on in the literature, can be categorized into three major groups, as was done by Huang et al. [12]. The first source is a monopole source resulting from the blade motion. The second is a dipole source which is caused by the pressure fluctuations on the surface of the blade, and the third source is a quadrupole source having its origins in the turbulent flow. Others categorize the sources in different ways, though all can be listed in the above groups.

The noise spectrum of turbomachinery typically consists of a broadband noise and tonal components, which are harmonics of the Blade Passing Frequency (BPF). Over the years many technological advances have been made in reducing the tonal noises, and because of this the BNS is now becoming one of the major contributors to the noise in certain parts of the industry [5]. This makes the further investigation of the BNS a logical step. According to [12], the work of Sharland [14] gave three possible mechanisms for the BNS of an axial flow fan. These are the unsteady blade surface pressure of the turbulent boundary layer, the unsteady vorticity shed from the trailing edge, and the random inlet flow fluctuations. [12] also mentions [15], where Longhouse found that vortex shedding from the blades and tip leakage vortices interacting with the blade inner span or a neighbouring blade are the dominant BNS. Later research also supports this [12, 16 and 17]. While in [18] the interaction of the tip leakage vortex, not with the neighbouring blade, but with the rotor wake is shown to be a source of noise. In the work of Brooks et al. [19] different airfoil self-noise noise sources are described. Airfoil self-noise is described as being due to the interaction between an airfoil blade and the turbulence produced in its own boundary layer and wake. The first of these sources is given as being a result of a turbulent boundary layer, occurring at a high Reynolds number, which can develop over most of the airfoil and produce noise as it passes over the trailing edge. The second is said to occur at a low Reynolds number, when the laminar boundary layer instabilities result in a noisy vortex shedding from the trailing edge. The third is

due to shed turbulent vorticity noise, given as occurring at low nonzero angles of attack, while at larger angles large-scale separation (also named deep stall) causes noise. Self-noise sources due to vortex shedding in the small separated flow region caused by a blunt trailing edge and the tip vortex noise are also mentioned. All of these categories can be subcategorized into the three major groups given in [12], but are brought to the attention of the reader, since the present paper focuses on the BNS.

3. CFD MODEL

In an earlier effort to investigate the aerodynamic effects of FSK, a CFD investigation was conducted at the Budapest University of Technology and Economics Department of Fluid Mechanics [2, 20 and 21]. In this investigation, FLUENT 6.2.16 [13] was used to make Reynolds-averaged Navier-Stokes (RANS) steady-state simulations on two comparative rotors, one being of FSK and the other being USK. These simulations utilized the standard $k - \varepsilon$ turbulence model and the enhanced wall treatment of FLUENT. The domain extent was one blade pitch, taking into account the periodicity of the model. This domain extends to approximately 8 and 3.5 midspan axial chord lengths upstream and downstream of the rotor blading in the axial direction, respectively. The nose cone area of the domain is given as irrotational, while the hub and the one blade in the middle of the domain are given as having a rotational velocity. The air in the domain was defined as having a constant density. The inlet boundary condition was prescribed as a swirl-free uniform axial inlet condition, with the inlet turbulence intensity being given as 1%, and the casing diameter being given as the hydraulic diameter. A zero diffusion flux was given for the outlet boundary. The discretization of convective momentum and turbulent quantity fluxes were carried out by the Quadratic Upstream Interpolation for Convective Kinematics (QUICK) method. It is noted here, that though some would question the use of commercially available software for turbomachinery research, the results of these simulations and many others ([10, 11, 22 and 23], all using FLUENT) suggests that reliable results can be obtained using commercially available codes, such as FLUENT. More information on the model parameters, including geometric information, can be found in [2, 20]. The results of the CFD investigation were validated in [2, 21]. The results of [22] and [24], in which a fair agreement between the CFD and the measurement results were found during the validation of the flow field, which was done in order to validate the Computational Aeroacoustic (CAA) investigations, encouraged the authors to use these CFD simulation results for further CAA investigations.

4. ACOUSTIC MODEL

In CAA, there are different methods which can be used in order to learn about the acoustical properties of a system. It is possible to use Direct Numerical Simulations (DNS) or Large Eddy Simulations (LES) in order to solve the unsteady compressible Navier-Stokes equations in the entire domain, known as Direct Noise Computations (DNC). Another method uses DNS, LES or unsteady RANS together with an acoustic analogy, giving results for the far-field noise. While in a third method, one can apply a BNS model to a steady-state RANS CFD simulation in order to learn about the BNS [13, 25].

In using BNS models, statistical turbulence quantities computed from RANS results, in conjunction with semi-empirical correlations and Lighthill's acoustic analogy, can give information as to the source of the broadband noise [13]. In this way the source terms can be used to find the locations of the noise sources and to compare them, which shows that BNS models provide a useful means by which to determine the prominent noise generating regions in a flow domain, as well as giving a means by which to compare different variations of a design in order to screen out noisier variations and identify the primary sources of the noise [24, 25].

There are four different BNS models available in FLUENT, and it was decided that two of those, the Proudman's Formula Model and The Boundary Layer Noise Source Model, would be investigated here. These two were chosen, because they complement each other by giving the dipole and the quadrupole sources in the form of acoustic power. The Proudman's Formula BNS model of FLUENT is a simple yet very useful way of determining the local contribution to the total acoustic power from quadrupole sources. This formula for the acoustic power generated by isotropic turbulence, as seen in Eq. (1), gives the results in the form of acoustic power due to unit volume of isotropic turbulence (P_A).

$$P_A = \alpha_\varepsilon \rho_0 \varepsilon \left(\frac{\sqrt{2k}}{a_0}\right)^5 \left[W/m^3\right] \qquad (1)$$

In this formula, α_ε is a rescaled constant, which is set to 0.1 in FLUENT, ρ_0 is the ambient density, ε is the dissipation rate, k is the turbulent kinetic energy, and a_0 is the speed of sound [13]. The results can also be viewed in sound power level.

The other BNS model, which was investigated, is the Boundary Layer Noise Source Model. This model is useful for investigating sound generated by turbulent boundary layer flow over a solid body at low Mach numbers. In this model Curle's integral is used to approximate the local contribution per unit surface area of the body surface to the total acoustic power (P_A), as seen in Eq. (2).

$$P_A = \int_S I(\vec{y}) \, dS(\vec{y}) \qquad (2)$$

Where

$$I(\vec{y}) \equiv \frac{A_c(\vec{y})}{12\rho_0 \pi a_0^3} \overline{\left[\frac{\partial p}{\partial t}\right]^2} \qquad (3)$$

$A_c(\vec{y})$ is the correlation area, $S(\vec{y})$ is the integration surface and $I(\vec{y})$ is the sound intensity per unit area of the surface [13].

Here the mean-square time derivative of the surface pressure and the correlation area are approximated in terms of turbulent quantities such as k, ε and wall shear. These results can also be given in sound power level.

The other two BNS models available in FLUENT give the source terms of the Linear Euler Equations and of the Lilley's Equation, and will therefore be investigated separately at a later time.

5. RESULTS

In looking at the USK and FSK rotors side by side, the acoustic effects of the FSK can be examined. The first topic to be examined among the BNS which are listed above is the tip leakage vortex.
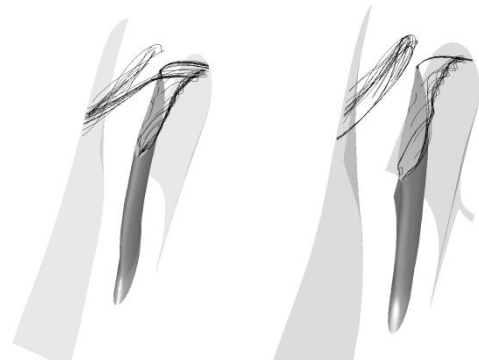

Figure 1. Pathlines of the blade tip leakage (black lines) for the USK (left) and FSK (right) rotors. The light grey walls show the periodic boundaries, with the blades being viewed from upstream. The darker grey shows the blades, with the pathlines being released from the blade tip profiles. The blades are rotating in the counter-clockwise direction.

In [2] it was given that with FSK the aerodynamic benefits of forward sweep can be utilized while improving the mechanical properties of the blade, and therefore it is expected that the tip leakage advantages of forward sweep are valid for FSK along a large part of the operation range, as

given in [7]. It can be seen for the USK, by viewing the pathlines in Figure 1, that the flow from the tip leakage near the trailing edge of the neighbouring blade penetrates the tip area, while it does not in the FSK case. This is referred to as double-leakage in [26]. The reason for this is that the FSK case has a more uniform chordwise loading and therefore a weaker leakage flow [2], the development of which is also moved farther back along the profile since the point of minimum pressure is moved farther back as a result of the FSK [7].
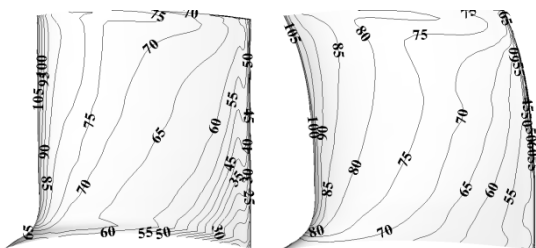
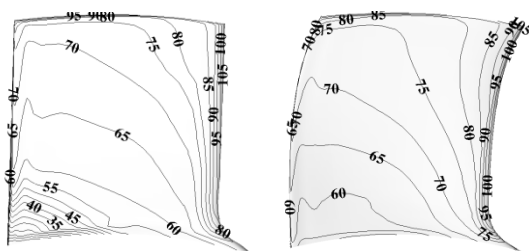**Figure 2. SS surface acoustic power level of the USK (left) and FSK (right) rotors.**

Figure 3. PS surface acoustic power level of the USK (left) and FSK (right) rotors.

In Figures 2 to 3 can be seen the Suction Side (SS) and Pressure Side (PS) surface acoustic power level results from the Boundary Layer Noise Source Model. In the investigation of the effect of the tip leakage vortex on the surface acoustic power level of the PS of the neighbouring blade (Fig. 3), it was found that the effect is not present, with the leakage flow from near the trailing edge not intersecting, but instead passing over the neighbouring blade (double-leakage). As was stated earlier, the works of Longhouse [15, 16] and Fukano et al. [17] show that the interaction of the tip leakage vortex with the PS is one of the dominant noise sources for axial flow turbomachinery, though similar results are explained slightly differently in the work of Bianchi et al. [18], who summarized a great deal of literature about tip leakage noise. The summary lists the works of Marcinowski [27], saying that tip clearance increases broadband noise, Mugridge et al. [28], reporting on an optimum tip clearance at which broadband noise is a minimum due to the countervailing effects of the tip leakage flow and the passage vortex, Kameier et al. [29] and Holste et al. [30], reporting that with the smallest possible tip

clearance, noise in a limited frequency range near the BPF was reduced. Bianchi et al. also stated that many interaction mechanisms between sources of turbulence and fan rotor components have been identified as the cause of noise signature, with the interaction between the endwall boundary layer and the rotor tip being the most significant, in view also of the aerodynamic interaction that tip leakage flow exerts on the wake and secondary flow. Bianchi et al. then proceeded to link a noise source to the interaction of the tip leakage vortex and the rotor wake, with the help of measurements. This shows that, just as in this case, the tip leakage flow is a source of noise, though not necessarily due to the interaction with the adjacent blade. This can be seen in the contour plots of the surface acoustic power level on the casing of the fan in Figure 4 showing that the noise sources found in the wake of the FSK rotor have a smaller acoustic power level than the USK. This can also be seen in the iso-surface contours in Figure 5, which depict the 50 dB acoustic power level iso-surfaces as they extend from the blade tip regions, with the USK extending farther downstream.
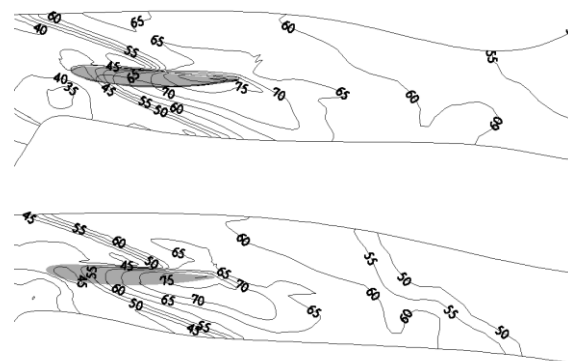

Figure 4. Surface acoustic power level results on the casings of the USK (top) and FSK (bottom) rotors, with the top of the blade shaded in the background. Looked at from outside the casing.

In further comparing the surface acoustic power level results for the USK and FSK rotors in Figs. 2 to 3, in order to investigate the self-noise BNS, the highest levels can be seen on the leading edges, where the USK case has a maximum value of 113 dB and the FSK case has a maximum value of 115 dB. The minimum levels can be found on the trailing edges, near the hub, where the USK case has a minimum value of 0 dB on the PS and the FSK case has a minimum value of 36 dB.
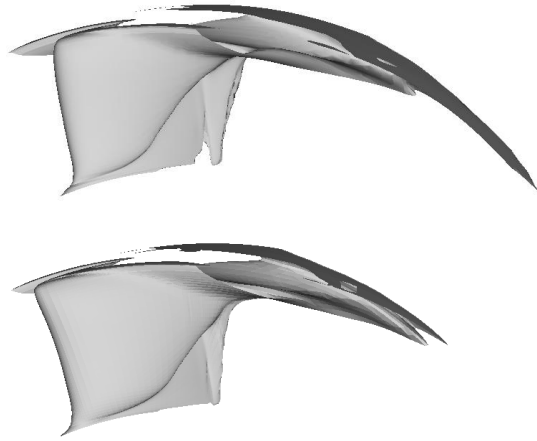
Figure 5. 50 dB iso-surface acoustic power level results for the USK (top) and FSK (bottom) rotors, as seen on the SS.

In focusing on the tip section of the leading edge, it can be found that the maximum acoustic power level is due to the stagnation point. The reason for the near tip section of the leading edge having a higher value than the hub section is due to the fluid having a locally higher velocity magnitude. This can be seen in the aerodynamic investigations of this rotor by Vad et al. [2] and Horváth et al. [21], where the upstream flow coefficient shows an increase in the axial velocity near the tip of the blade, just outside of the boundary layer. It is also shown in this work that the FSK tip area of the blade protrudes into the upstream relative flow field and carries out work in advance, as compared to the blade sections at lower radii, resulting in an increased velocity and the change of the flow incidence angle along the span, as compared to the USK case.
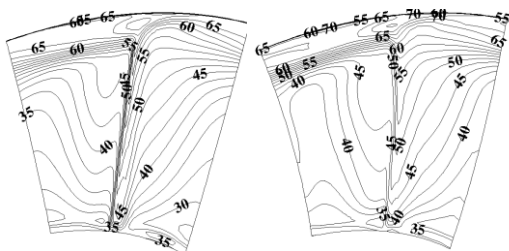

Figure 6. Acoustic power level results downstream of the USK (left) and FSK (right) rotor. The blade wake is in the middle of the plane, with the PS being to the left and the SS being to the right of the blade.

This change in the angle of attack of the blade caused the FSK to have increased losses, especially on the SS, as shown in [2]. This brought about a blade root suction side stall, as well as a passage vortex, which are found near the hub of the SS [2]. When looking at the surface acoustic power level in this area (Figs. 2 to 3) and the acoustic power level results at 26.6% midspan axial chord length downstream of the rotor in Figure 6, it can be seen that the FSK case is locally louder than the USK case. These results agree with the results of Bianchi et al. [18], where one of the noise sources is interpreted as being caused by the SS stall interacting with the passage vortex, as well as showing that the SS stall and the passage vortex resulting from the FSK are acoustically unfavourable.

The 20% span contour plots of the acoustic power level, as seen in Figure 7, show that the flowfield near the hub of the FSK is unfavourable from an aerodynamic as well as acoustic point of view and the noise source is wider and spreads all along the length of the blade and in the wake. This is resulting from the change in the flow incidence angle, as stated above. It can also be seen in Figs. 2 to 3 that the FSK case has a higher surface acoustic power level along a large portion of the span. Therefore these results show that the unsteady blade surface pressure of the boundary layer BNS can also be seen in these examinations and that in this case the FSK is less favourable, with the angle of attack leading to shed turbulent vorticity from the trailing edge as discussed in [19], and which will be discussed later in this report. With some geometrical modifications, or in other words by compensating for the increased velocity with the incidence angle of the FSK blades, this could be improved though.
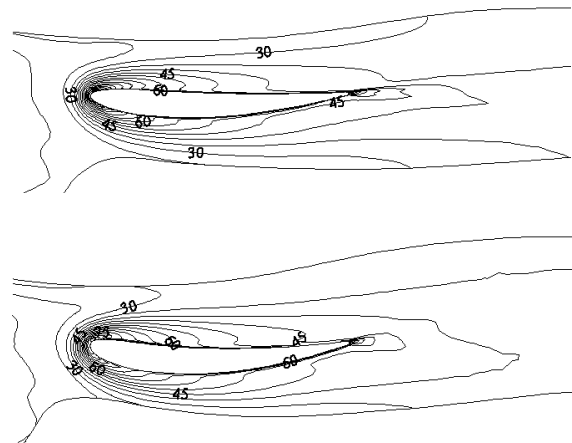

Figure 7. Acoustic power level at 20% span for USK (top) and FSK (bottom) rotor. The PS is above the blade and the SS is under the blade.

In examining the two remaining BNS discussed earlier, the unsteady vortices shed from the trailing edge and the random inlet flow fluctuations, it should be remembered that the simulations do not show the shedding of unsteady vortices and random flow fluctuations clearly due to the nature of the RANS simulation, the modelling of turbulence, the

inlet boundary condition and the periodic boundary condition, but instead show an area of higher k. An unsteady simulation along with a precisely defined inlet boundary condition and geometry would be necessary in order to see the interaction of upstream vortices with the blades, along with those being shed from the trailing edge. It should also be noted that since k can be used to define the boundary layer thickness and the blade wake width of the simulated results, as well as also being used here in the calculation of P_A, figures showing the boundary layer thickness and blade wake have been neglected in order to save space.

The trailing edge noise can be seen in the wake of the blade in Fig. 6, where the FSK has a wide zone of larger magnitude along a large portion of the span. In the literature though, Ohtsuta et al. [8] stated that FSK results in lowering the trailing edge noise over the normal operating range. Therefore, for trailing edge noise, the FSK case should be advantageous as compared to the USK. An explanation for this difference is given in [19] and [31]. Among the discussed possible airfoil self-noise mechanisms listed in [19], it is given that shed vorticity can develop for a nonzero angle of attack. It is also given in [31], for the analytical as well as experimental results, that the trailing edge noise increases with boundary layer thickness and the resulting blade wake width. Therefore, the investigated FSK case, where the boundary layer thickness as well as the resulting blade wake width was much thicker as compared to the USK case, was noisier. This was resulting from the angle of attack. As was stated earlier, this can be compensated for with some geometrical corrections. In this section pertaining to trailing edge noise, the earlier findings regarding the interaction of the tip leakage flow and the wake should also be mentioned along with the interaction of the passage vortex and the blade root suction side stall.

It is stated in a large amount of literature [6, 11, 12, 22 and 32] that random inlet flow fluctuations are one of the most dominant noise sources for low speed axial flow turbomachinery. The random inlet flow fluctuations come about as a result of the upstream geometry and flow conditions. Therefore if adequate boundary conditions are given and the geometry is well modelled, the effect of the upstream turbulence intensity can be seen on the blade as measured in [18]. In the USK and FSK cases, both of the models have the same upstream conditions and geometries, and therefore this cannot be thoroughly investigated. Therefore no conclusions can be made in comparing these two blade geometries with respect to the random inlet flow fluctuations, though a separate investigation will be made in order to compare the acoustic power levels at different turbulence intensities.

6. CONCLUSIONS

Two fans, one being the USK datum case and the other the FSK case, were acoustically investigated using CFD and two BNS models in order to view BNS and compare the two cases. Table 1 summarizes the results of the investigation.

Table 1. BNS results for the USK and FSK.

BNS	Results
Tip leakage vortex	FSK is the better of the two cases, since the tip leakage advantages of forward sweep are kept with FSK.
Passage vortex and blade root suction side stall interaction	USK is the better of the two cases, since the passage vortex and SS stall interact forming a BNS, though this BNS is not dominant.
Unsteady blade surface pressure	Higher surface acoustic power levels are realized along a large portion of the span of the FSK, due to the unfavourable flow incidence angle making the USK the better of the two cases, though this can be compensated for in the FSK by changing the incidence angle.
Trailing edge noise	USK is the better of the two cases, though the FSK should be better according to the literature. This is also resulting from the angle of attack, as it ruins the expected FSK trailing edge noise properties. (The interaction of the tip leakage flow and the wake as well as of the passage vortex and the blade root suction side stall could also be listed here.)
Random inlet flow fluctuations	No conclusions could be made based on these results, since a comparison of the acoustic power level at different turbulence intensities needs to be investigated.

As can be seen in the table, all the different BNS can be investigated using the Proudman's Formula Model and The Boundary Layer Noise Source Model available in FLUENT, and therefore can be used to make comparative BNS investigations of different fan models. The methodology provided in this study can also be applied in other comparative studies, in order to make quick and cost effective comparisons between the acoustic characteristics of different fans.

In the present comparison results of the USK and FSK cases, examining one of the most dominant BNS, the tip leakage vortex, the FSK is the better of the two cases. It can also be seen that the most dominant source according to the literature, the random inlet flow fluctuation, was not thoroughly investigated here, since the upstream conditions of both simulations were the same, though a separate investigation will be made in order to compare the USK and FSK for different inlet turbulence conditions. In examining the remaining three BNS, it was found that the FSK, though expected to be, was not consequently the better of the two. The angle of attack was the cause of this and methods for remedying this problem were suggested. It is expected that with these remedies the FSK will be the better of the two cases in all categories. These results therefore demonstrate that the FSK has a positive impact on rotor acoustics.

In the further investigation of the use of BNS models for comparing different fan designs, the authors will compare the other BNS models available in FLUENT to those investigated here, in order to see which can be utilized the best. It is also planned that the results of this investigation will be used to refine the mesh in certain areas of the domain for use in unsteady simulations. In this way an investigation of the details which are lost in using steady state results will be examined, evaluating whether the lost information is crucial, or the present results are sufficient for designing fans. The steady state CFD simulations will also be re-evaluated in order to utilize the turbulence modelling advantages of the newer version of FLUENT 12.0. The use of a phased array microphone system is also planned for the near future, in order to compare the simulation results to acoustic measurements. In using the BNS models for comparing turbomachinery, the authors have realized that all the noise sources of turbomachinery, even including the tonal components, can be qualitatively investigated in order to compare different fan designs. Therefore a separate investigation of the tonal noise components, using the BNS models, is also planned.

ACKNOWLEDGEMENTS

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