PRORAČUN NIVOA BUKE GENERISANE PROTOKOM VAZDUHA U AKTIVNO KONTROLISANOM VAZDUŠNOM KANALU SA USMERIVAČIMA VAZDUHA OBLIKA AEROPROFILA

PREDICTION OF AIRFLOW-GENERATED NOISE IN ACTIVELY CONTROLLED DUCT WITH AIRFOIL VANES

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U mnogim KGH sistemima, vazdušni kanali se koriste za usmeravanje vazduha do i od sistema koji se opslužuju. Generalno, diskontinuiteti, grananje, turbulentncija u kanalima rezultiraju stvaranjem buke i gubitkom statičkog pritiska. Na buku izazvanu radom KGH sistema utiču raspored kanala, veličina kanala, brzine protoka vazduha, kompletna konstrukcija sistema a dozvoljeni nivoi buke regulisani su mnogim industrijskim standardima.

U ovom radu istražen je uticaj aktivno kontrolisanih usmerivača vazduha oblika profila (NACA 2412) u aktivno kontrolisanom sistemu na nivo buke. Usmerivači vazduha oblika aeroprofila utiču na vibracije sistema, buku, pad pritiska i shodno tome utiču na zdravstvene i bezbednosne zahteve.

Izračunavanje buke generisane protokom postiže se izvođenjem CFD simulacije primenom nekompresibilnog LES proračunskog modela zajedno sa akustičnom analizom strujanja u vazdušnom kanalu. Numerički modeli su razvijeni za različite položaje usmerivača vazduha i napadne uglove pri malim Maha-ovim brojevima unutar operativnog opsega aktivno kontrolisanog sistema.

Predviđeni nivoi buke eksperimentalno su provereni merenjem buke u blizini usmerivača vazduha, za različite brzine protoka, položaj usmerivača i konstrukciju kanala. Utvrđeno je da dizajn i položaj aktivno kontrolisanih usmerivača vazduha utiču na nivo buke u operativnom okruženju kanala za protok vazduha.

Ključne reči: *vazdušni kanali, vibracije, buka, usmerivači vazduha oblika aeroprofila, bezbednost na radu*

In many HVAC systems, ductwork is used to reticulate the air to and from the systems to be served. In general, discontinuities, bevel branching, flow vanes, turbulent flows in ducts result in the generation of flow noise and a loss of static pressure. The noise induced by the HVAC system operation is affected by the layout of the ductwork, ducts size, airflow velocities, complete system construction and the noise levels allowed are regulated by many industrial standards.

In the present work, the impact of airfoil shaped (NACA 2412) turning vanes, in an actively controlled system on noise level is investigated. Airfoil shaped vanes affect system vibration and pressure drop and consequently impact health and safety requirements.

Computation of flow generated noise is accomplished by performing CFD simulation deploying unsteady incompressible LES coupled with acoustic analysis. Computation models are developed for different positions of airfoil vanes and angles of attack at low Mach numbers within the operational range of the actively controlled system.

Predicted sound levels are experimentally verified by noise measurement in the vicinity of airfoil vanes for different flow velocities, vanes positions and construction. It was found that design and position of the turning vanes affects noise levels in the operational surrounding of the airflow duct.

Key words: *ductwork, vibration, noise, airfoil vanes, safety*

1 Introduction

In HVAC systems, ductwork is used to reticulate the working fluid to (and from) the aeras of the system to be served. The noise level requirements of the areas to be served can affect the design of the ductwork, the size of the ducts and the extent of noise attenuation required. The cost of the ductwork system, operational costs and the cost of space for the ductwork can all be increased as a consequence. Because of the computational effort involved, for in the noise level prediction requirements are often given limited attention. In this paper, main focus is given to noise prediction in an actively controlled duct, with airfoil shaped vanes its and transmission to adjacent (work) spaces. Noise that arises from the equipment (and all of its components) is an important part of the complete system design. The placement of equipment imperatively must consider the impact of equipment generated noise and involves consideration of noise and vibration. Adding bends, air-flow vanes, straight ducts, system components for turbulence reduction can reduce noise as air speed increases (in different regimes of system modes of operation). Ducts are designed to maintain the maximum velocity of working fluid with minimal noise increase. Poorly executed designs can cause noise generation by the duct-

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work system, which may lead to violation of standards and regulations for system noise emission followed by endangerment of work safety. The control of noise is a major issue which requires effective of acoustical analysis.

International standards describing basic methods for determining sound power levels are: ISO 3741 to ISO 3747 (sound power level determination using sound pressure level measurements), ISO 9614-1 to ISO 9614-3 (sound power level determination using sound intensity measurements), ISO/TS 7849-1 and ISO/TS 7849-2 (sound power level determination using vibration measurements). These standards specify methods for determining the sound power level and the accuracy, characterized by the reproducibility of the method, system design and mounting conditions, and the uncertainty associated previously mentioned conditions. The standards mentioned above differ in their range of applications and their requirements with regard to the test environment since some machinery (or components) equipment and products emit high-frequency noise, which can be broad-band noise, narrow-band noise or discrete tones.

In the present analysis the impact of position (angle of attack) of the turning airfoil (NACA 2412) vane in an air flow duct on the noise increase is investigated. HVAC turning vanes are devices inside of mechanical ductwork used to direct air inside a duct where there is a change in direction, by reducing resistance and turbulence. The effectiveness of airfoil type vanes, in order to reduce the pressure-drop and the vibrations in the air ducts was analyzed in [1-2]. In critical zones, where high vibrations and turbulence is sought, the airfoil vanes are located. These vanes are actively controlled, by optimally determining airfoil vanes angle of attack (position of the airfoil in the respect to the incoming air stream). Flow parameters, such as velocity and static pressure are constantly monitored at the inlet and the outlet of the critical zones. Based on the implemented algorithm, that was developed using CFD analysis of the concrete system the rotation of the vanes around z axis, optimal AoA (angle of attack) is assumed, rendering minimal pressure drop and reduced system vibrations. Microcontroller (s) acquire input from the DSP pressure sensors and pitot tubes at the inlet, inputs from the same kind of sensors at the outlet of critical zones, and by means of stepper motor directly attached to airfoil shape duct vanes, position the vanes in to optimal position to obtain minimal pressure drop at the outlet an reduce complete system vibrations. The main components of actively controlled air duct (segment) with airfoil vanes are presented in the Figure 1.

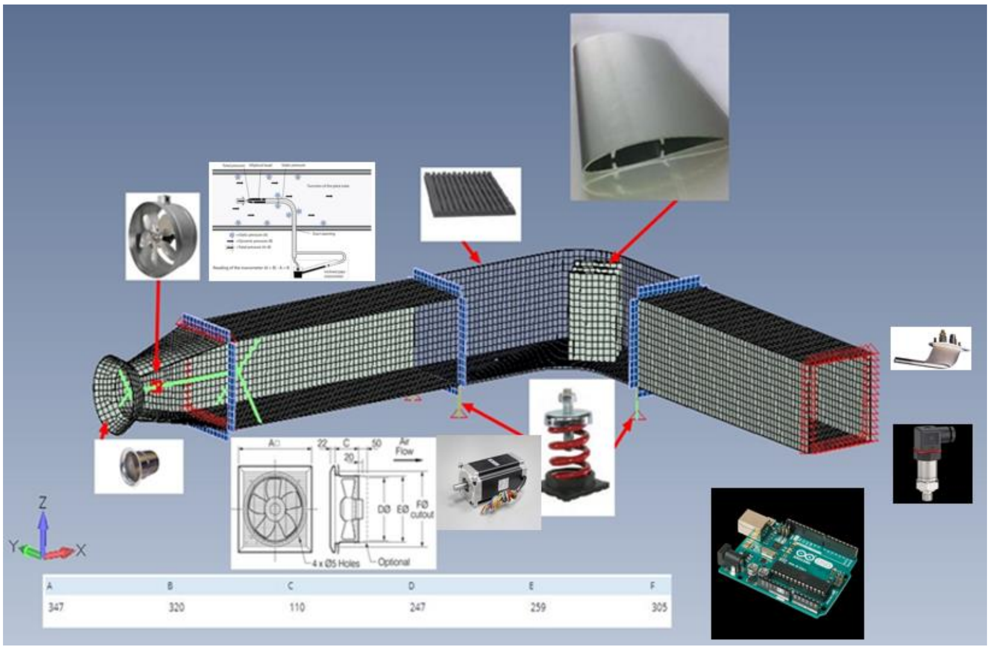

Figure 1: Actively controlled air duct with airfoil vanes-main components schematic

2 Numerical Analysis

In order to obtain noise level rise as a result of the deflection of airfoil vanes (AoA change) the CFD analysis is performed, followed by the acoustic analysis and the experiment verification. Three sources of noise associated with mechanical ventilation systems can be identified: fan noise, break out noise and flow generated noise. To perform the acoustic analysis of a deflected airfoil vane in the air duct, pressure and velocity fields have to be obtained. Following system equations were solved for the analyzed flow field:

Averaged continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho U_i\right) = 0 \qquad (1)$$

Reynolds vector equation:

$$\frac{\partial}{\partial t}\left(\rho U_i\right) + \frac{\partial}{\partial x_i}\left(\rho U_i U_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu_f S_{ij} + \tau_{ij}\right) + \rho F_i \qquad (2)$$

and the averaged energy balance equation:

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x_i}\left(\rho U_j H\right)=U_i\frac{\partial P}{\partial x_i}+\mu_f\psi_\mu(U_i)+\mu_f\psi_\mu(u_i)+\frac{\partial}{\partial x_i}\left(af\frac{\partial H}{\partial x_i}-\rho\overline{hu_i}\right) \tag{3}$$

Since the air, as a primary fluid, considered to be a perfect gas, its density can be determined using the equation of state:

$$\rho=\frac{P}{RT} \tag{4}$$

and the value of specific enthalpy is defined by the expression:

$$H=c_pT \tag{5}$$

Following the generalized and corrected Boussinesq's hypothesis, which introduces the notion of turbulent (vortex) dynamic viscosity μ_t by connecting Reynolds stresses and the strain rate tensor S_{ij}, and which for, in numerical terms, incompressible Newtonian fluid flows, reads:

$$\tau_{ij}=\mu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\frac{2}{3}k\delta_{ij}=\mu_t S_{ij}-\frac{2}{3}k\delta_{ij} \tag{6}$$

The initial Reynolds vector equation, now modelled, takes the following form:

$$\frac{\partial}{\partial t}(\rho U_i)+\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\mu_f+\mu_t\right)S_{ij}-\frac{2}{3}\rho k\delta_{ij}\right]+\rho F_i \tag{7}$$

Also, in all numerical simulations, the viscosity dissipation functions in the energy balance equation $\mu_f\psi_\mu(U_i)$ and $\mu_f\psi_\mu(u_i)$ are modelled using turbulent dynamic viscosity:

$$\mu_f\psi_\mu(U_i)+\mu_f\psi_\mu(u_i)=2\mu_t S_{ij}S_{ij} \tag{8}$$

The vector of enthalpy of fluctuation flow, following the simple gradient method, is modelled as:

$$\rho\overline{hu_i}=\frac{\mu_t}{\mathrm{Pr}_h}\frac{\partial H}{\partial x_i} \tag{9}$$

which allows writing the energy balance equation as:

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x_j}\left(\rho U_j H\right)=U_i\frac{\partial P}{\partial x_i}+2\mu_t S_{ij}S_{ij}+\frac{\partial}{\partial x_i}\left[\left(\rho a_f+\frac{\mu_t}{\mathrm{Pr}_h}\right)\frac{\partial H}{\partial x_i}\right] \tag{10}$$

Previous system of equations was numerically solved using Large-eddy simulation (LES) [3] which was originally developed for simulating atmospheric flows. Taking into account the advances in computer technology LES algorithm has become one of the most promising and successful methodology for simulating turbulent flows. However, apart from the computing power, significant challenges still remain for LES to reach a level of maturity that brings this approach to the mainstream of engineering and industrial computations being one of the reasons for which the results for the pressure and velocity fields, in this research were carried out with k-ε turbulent model as well. Parameters for the k-ε model used in the present flow analysis are presented in the Table 1.

Table 1: k-ε model turbulent model parameters

Pr_k	Pr_ε	$C_D C_\mu$	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	$C_{\varepsilon 3}$	k	Pr_h	Sh_t
1,0	1,718	0,15	1,67	2.05	1,0	0,34	0,01	0,81

Computational domain of the straight segment of the actively controlled air duct with airfoil vane deflected at 20^0 is presented in the following figure (Figure 2.):

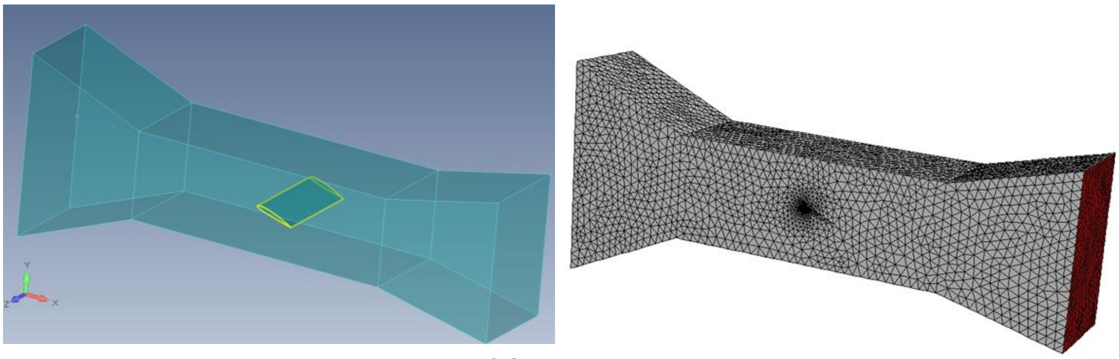

Figure 2: Computational domain of the straight segment of the actively controlled air duct with airfoil vane deflected

To analyze the effect of the deflected vane CFD analysis is performed in the air duct without the vane and the airduct with the airfoil vane at the AoA of 20^0. Pressure and velocity fields within the computational domain of interest are obtained as a prerequisite for the acoustic analysis. Static pressure fields are presented in the following figure (Figure 3.):

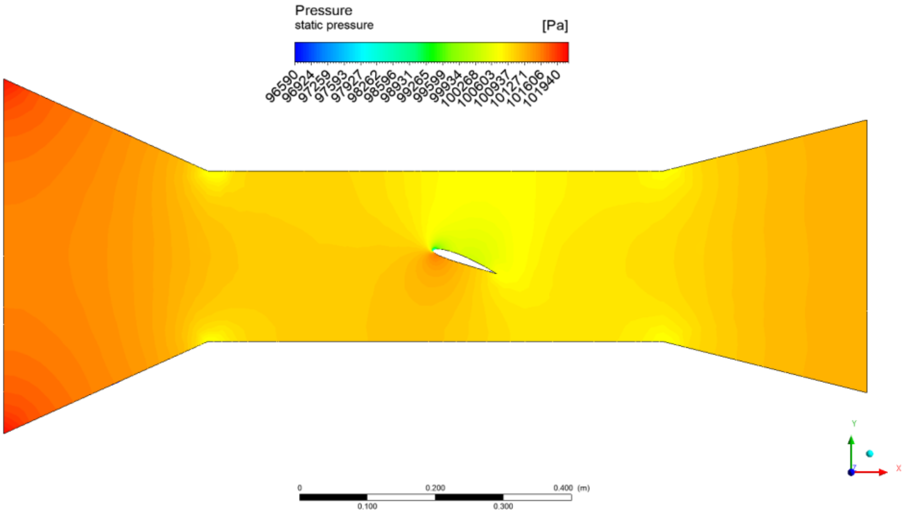

Figure 3: Pressure fields in Computational domain of the straight duct segment of the actively controlled air duct with airfoil vane deflected.

Airflow-generated noise arises when air travelling along a duct encounters a discontinuity, such as a damper or change· of geometry, which disturbs the flow and results in the generation of localized turbulence. The work required to generate this turbulence is manifest as a drop in static pressure across the discontinuity. Some of the turbulence energy is converted into noise. In a straight segment of the duct the noise generated by the air flow is a function of airflow velocity and cross-sectional area of the duct at that segment. Generated noise can be calculated using following equation:

$$L_N=10+50 \log(v)+10 \log(A) \tag{11}$$

Where, v is air flow velocity, A is cross sectional area and L_N is sound power level expressed in decibels (dB). Using equation 11. for the straight duct of rectangular duct section of h x d = 45 x 40 [cm] the estimated noise level due to air flow of 25 m/s at the inlet is 83.5 [dB]. Unfortunately, the engineering formulae employed frequently produce inaccurate results.

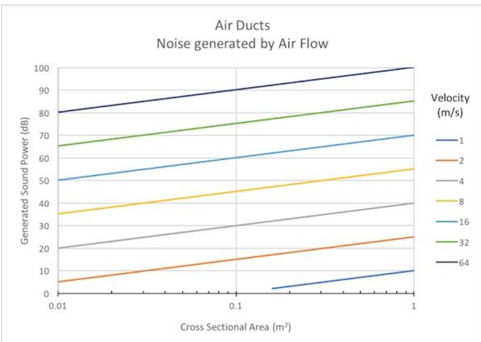

Figure 4: Noise generated by air flow in a straight segment of the duct [4]

The flow field calculated for the most critical case which is the deflection of the turning vane at the Max AoA, and hence the noise contribution from the deflected airfoil vane is presented in the following figure (Figure 5.).

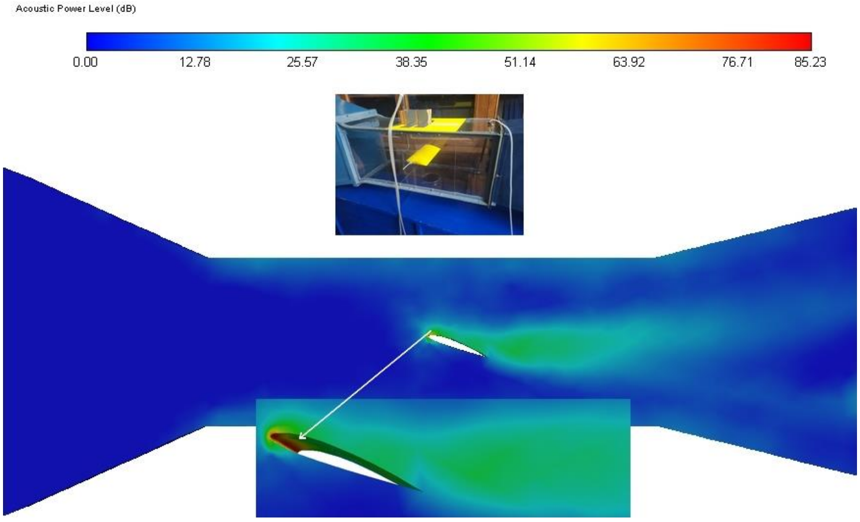

Figure 5: Noise generated by air flow in a straight segment of the duct, noise level at the leading edge

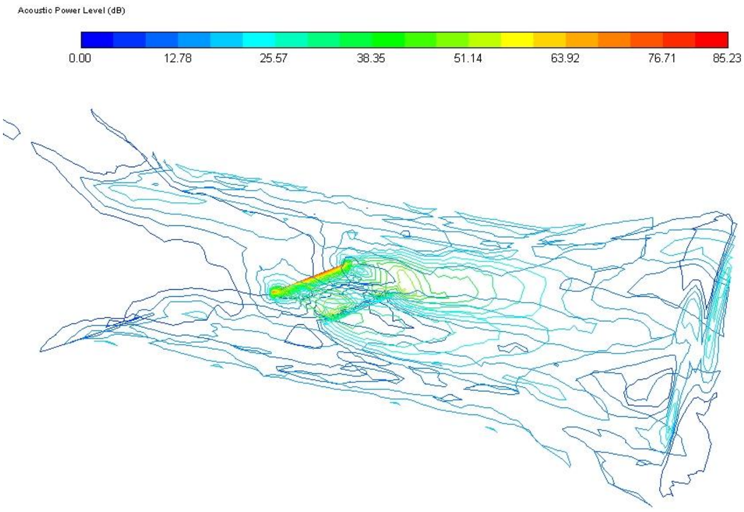

Figure 6: Noise generated by air flow in a straight segment of the duct, 3D Acoustic field

3 Experiment

The experiment was performed in a subsonic wind tunnel (closed type), with electrical power motor, capable of generating an air flow up to 30 m/s in working section of the wind tunnel. At the inlet, the pitot tube was installed and noise measurement was performed for velocities in the range of 5 – 25 m/s for different positions (angles of attack) of air foil vane. The pressure was constantly monitored at the outlet using dsp pressure sensor. All sensors were connected to data acquisition unit. The acoustic power level was measured in the vicinity of deflected vane, which was located in the center of working wind tunnel area. The cross-sectional area, where touring van was located was d x h = 400 x 450 [mm]. The acoustic power level was measured using Minilyzer ML1 - Handheld Audio Analyzer which was initially calibrated using Tecpel 336A sound calibrator.

After calibration procedure, the acoustic power levels were measured for the airflow in the straight section of the duct in the vicinity where touring vane will be located. The air velocity was gradually increased up to (stable) velocities of 25 m/s. [Figure 7 (left position)]

After the power sound levels were measured for air flow velocities in the range of 5 – 25 m/s, the airfoil vane was mounted in the airflow duct [Figure 7 (right position)]. As in previous case, the velocity was gradually increased till stabilized. The air foil vane was positioned in the air stream by change of the angle of attack in the range of 5^0 -20^0. The value of the angle of attack was verified using mechanical dial mounted on the side of the wind tunnel used for this experiment and the axis of airfoil rotation coincides with the longitudinal axis of the vane passing through the aerodynamic centers (for this series of airfoil, NACA 2412, it is located at 25 % measured from the leading edge of the vane).

For all cases and operational regimes (velocities and different angles of attacks) the sound level was measured. The most critical case, compared to the airflow with no vane for the velocity of 25 m/s is presented in the following figure (Figure 8.).

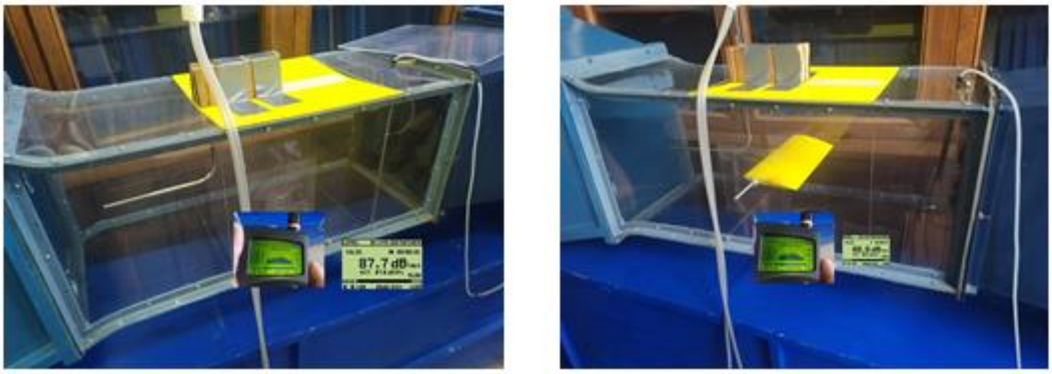

Figure 7: Noise generated by air flow in a straight segment of the duct, 3D Acoustic field

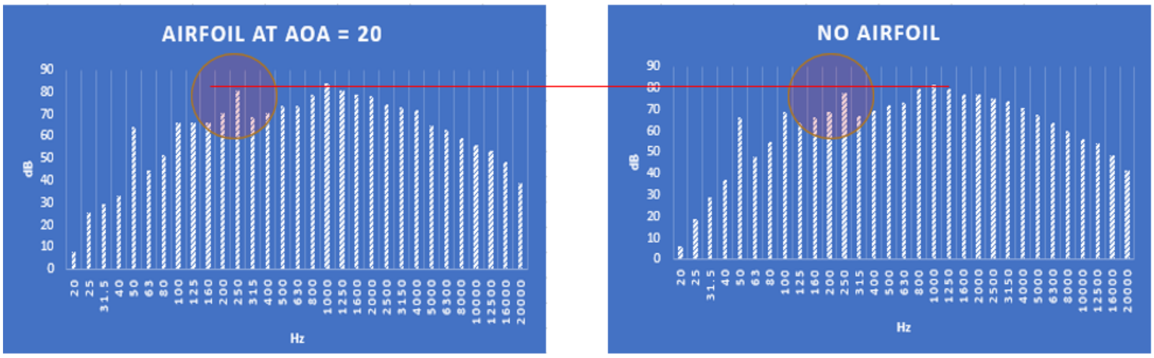

Figure 8: Noise generated by air flow in a straight segment of the duct, 3D Acoustic field

4 Conclusions and recommendation for the future work

In this research the impact of airfoil type turning vane in an air duct on noise levels is investigated. Sources of noise in airflow ducts can be numerous. These are fan noise, break out noise and flow generated noise to name most influential ones. By performing CFD and acoustic analysis the acoustic power levels were calculated for the case of duct straight segment followed by the calculations of the acoustic power levels for the duct with deflected vane in the shape of an airfoil (NACA 2412). CFD and acoustic simulations were verified by experimentation in the closed type subsonic, electrically powered wind tunnels.

It was found that apart from the velocity magnitude of the air flow, geometry and position (expressed through the angle of attack) of the airfoil vane contribute to flow generated noise in an air duct.

To accurately predict influence of the position of the turning airfoil vane on the airflow generated noise further testing is advised, since in the present test set up fan generated noise was relatively high for the system analyzed.

5 References

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