The evaluation of noise emitted by flow around the blade of HVAC system

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Abstract

The paper deals with aerodynamic noise generated at low Mach numbers by flow over a blade grill commonly used as a terminal diffuser of air-distribution systems. The aerodynamic noise of HVAC (Heating, Ventilating and Air Conditioning) systems is undesirable not only in residential buildings, office buildings, hospitals but especially in spaces with high acoustic demands such as TV or recording studios. Total sound is not the only one criterion which is evaluated by acoustics. The spectrum of the noise is significant criterion particularly the existence of discrete tones at acoustic spectra. The main challenge of this experiment was to build an experimental test stand with a requirement of low noise from the fan. The goal of the paper is to compare the acoustic spectra of sound power level, vibration of the blade generated by flow and the velocity fluctuation of turbulent flow behind the blade. The experiment is a part of the wider research into aerodynamic noise.

Key words: aerodynamic noise, blade grill, HVAC, Strouhal number

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1. Introduction

The important part of environmental engineering is the acoustic engineering of indoor or outdoor surrounding. The basic parts of acoustic engineering are acoustics of building engineering (the insulation of a construction), traffic noise, industry noise and the noise generated by sources of HVAC – heating, ventilating and air conditioning systems. This paper deals with aerodynamic noise generated by flow over a blade grill commonly used as a terminal diffuser of air-distributing system where the air velocity is not large, the flow velocity is up to 18 m/s (under $M = 0.053$). The aerodynamic noise of HVAC systems (Heating, Ventilating and Air Conditioning) is a negative side effect of air-distribution. The terminal diffuser is the part of the system most predisposed to emitting aerodynamic noise.

The main requirement for low noise emissions is low airflow velocity. However, this leads to larger dimensions of air-distribution systems. The main sources of noise in HVAC systems are ventilator and control elements, which can be dampened, however, it is not possible to dampen the aerodynamic noise of the terminal diffusers.

Aerodynamic noise is generated by turbulent flow in almost every air-distribution system, this is an unstable flow. For low Mach number it is possible to use Reynolds decompositions as a description of turbulent flow (for higher velocity it is appropriate to use Favre decompositions [1]). The Reynolds decomposition is a mathematical technique used to separate the average and fluctuating parts of flow variables (velocity, pressure, etc.). The density of the air for velocity under 70 m/s is considered as constant without fluctuations. The fluctuations of variables cause the aerodynamic noise emitted to the surrounding environment, which was described by Lighthill [2, 3]. The other source of sound could be from vibrations of the blade caused by turbulent flow. In such a case the generated sound could be dependent on the shape of the object and its construction. In the extensive experiment of King [4], flows with velocities of 30 and 60 m/s around the cylinder generated noise by fluctuations emerging behind the cylinder (Karman´s vortex) but the noise generated by surface vibrations of the cylinder was negligible. The proof of this observation is the constant result of the acoustic spectra in the Strouhal number range of 0.15 to 0.2, which was also confirmed by previous experiments [5,6,7]. A different issue is the noise generated by a blade, see Figure 1.

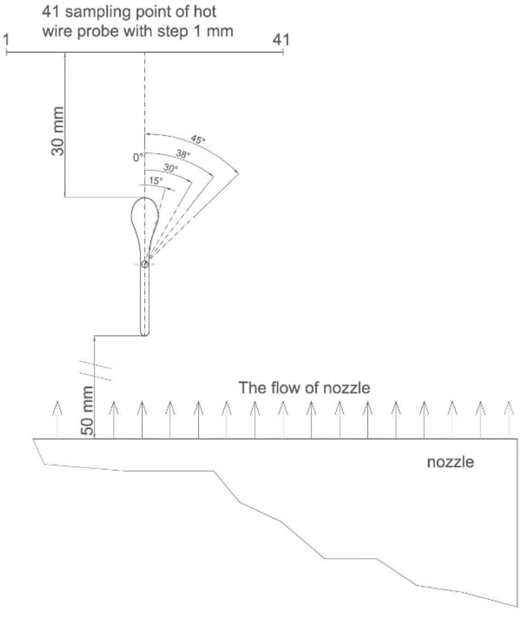

Fig. 1: *The cross-section of the hot wire anemometry at a distance 30 mm above the blade, this position of the blade is marked H.*

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The shape of the blade is not appropriate for low emission of noise, the thicker front part of the blade creates vortices (similarly to the cylinder) which in this case lean to the flat rear part of the blade. The flat part should reduce the generated vortices and decreases the emission of noise, however, the vortices cause vibrations of the blade, which generate the sound. The experiment with turbulent flow around a plate which generated sound caused by vibration of its surface was performed by Chou [8].

The goal of this paper is to compare the acoustic spectra of sound pressure level of aerodynamic noise generated by flow around the blade, vibration of blade generated by flow and the velocity fluctuation of turbulent flow behind the blade. The experiment is a part of the wider research into aerodynamic noise. It was measured only one blade in the airflow velocity 12 m/s in position H (thin edge against the flow), see figure 1, and D (rounded edge against the flow), and only for vertical position 0°. It continues the previous experiments [5,6,7] which referred to aerodynamic noise of the blades and cylinder. The air flow around the cylinder generates a peak of acoustic spectrum within the Strouhal number range of 0.15 to 0.2, as noted, which is not dependent on the material of the cylinder. However, it has been found that the air flow around the blade grill generates more peaks in acoustic spectra, i.e. for the Strouhal number range of 0.15 to 0.25, and also higher values 0.5 and 0.7. The peaks in acoustic spectra of the blade grill are discrete tones. There are three peaks in acoustic spectra for low velocity of air flow (under 8 m/s), and only one peak for higher velocity, within the Strouhal number range of 0.15 to 0.25.

2. The experimental test stand and methodology of evaluating

The experiment was performed on the experimental test stand. The airflow was generated by a centrifugal fan dampened by an absorb buffer for middle and high frequencies and an absorb chamber for low frequencies of noise.

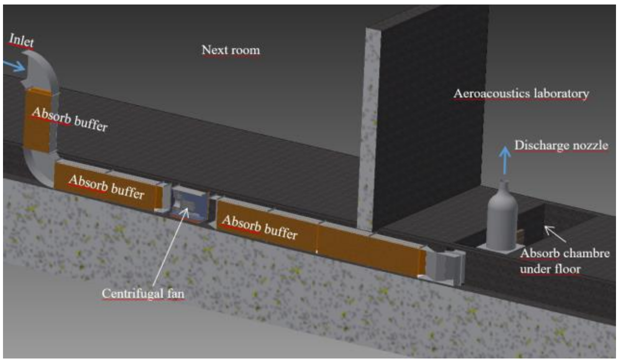

Fig. 2: *The cross-section of the experimental test stand.*

The experimental airflow outlet was the discharge nozzle with a diameter of 150 mm. It was situated in the acoustics laboratory which has highly absorbing walls and ceiling, the floor was reflective (concrete floor). See Figure 2 for the diagram of the experimental test stand which was supposed for the experiments with aerodynamic noise up to flow velocity 26 m/s in the nozzle with the uniform velocity profile. The tested object (e.g. blade) was positioned 50 mm above the nozzle and the background noise of the experimental test stand was only the aerodynamic noise of the nozzle, the noise from the fan was negligible.

The experiment was performed only with one blade which length is 500 mm. The experiment with blade was performed in the position H (see Figure 2) and D. Position H is typical for an inlet terminal diffuser of air-distribution systems. Position D (the rounded edge of blade against the direction of airflow) is common for an air exhaust.

The sound pressure level was measured 1 m from the experimental subject, below an angle of 45°, in eight positions around the centre of the nozzle. From the measured values the logarithmic average was calculated. There was a direct acoustic field from frequencies 80 Hz without reflected sound pressure level up to the distance 1 m from the centre of the nozzle. The sound pressure level was measured in FFT (Fast Fourier transform) with bandwidth 1 Hz, which was corrected for background noise caused by the nozzle. The final spectrum of sound pressure level of aerodynamic noise is considered from 100 Hz, because the noise generated by flow around the blade is dominant from this frequency. The noise spectrum is not defined under 100 Hz (where the aerodynamic noise of the nozzle is dominant). The spectrum was converted to Strouhal number.

The frequencies of the velocity fluctuations of turbulent flow were measured for the qualitative evaluation of the aerodynamic noise spectra. The hot wire anemometry Dantec stream line was used with 1D probe the type 55P11. The turbulent flow was evaluated by FFT analysis of the velocity fluctuations. The analysis of the flow field was performed at a distance 30 mm behind the blade in the section 40 mm with step 1 mm (in total 41 records for every measurement), as presented in Figure 1. The main vortex field behind the blade is approximately in the middle of the measured section. The sampling frequency of hot wire anemometry was 10 kHz with 20 000 samples (recording time 2 seconds). Matlab software was used for post processing of the velocity data and its description for Fast Fourier transform. The results of FFT post-processing is the dependence of the velocity amplitude on the frequency (range 1 – 5000 Hz), which was converted to Strouhal number.

The vibration of the blade was measured by 1D probe situated on the flat part of the blade outside the airflow. 1D probe measured dominant motion of the blade which is in horizontal direction according to a motion of the vortices behind the blade. The velocity of vibration was measured. The weight of the probe of vibration is 1 g, the weight of blade is approximately 50 g. It is possible that the natural frequency of the blade was changed by increasing of the weight, but this experiment is only for referring the properties of aerodynamic noise and correlation between the spectra of fluctuation, vibration and emitted noise. This is the first step to obtain deeper knowledge about this.

The shapes of the relative spectra are used as a comparison of the spectra of sound pressure level, velocity of vibration and velocity of fluctuation of turbulent flow. The relative spectra are calculated according to the equation (1). The amplitude of velocity fluctuation as a function of FFT was increased multiplied by 100 value for better presenting of shapes of the relative spectra in the diagram because the sound pressure level and vibration have different scales. The goal of this paper is only the comparison and similarity of the value of Strouhal number.

$$L_{j,rel} = L_j - L \tag{1}$$

The spectra sound pressure level, velocity of vibration and velocity fluctuation of turbulent flow were converted to Strouhal number according to the equation (2). A characteristic dimension of Strouhal number is thickness of rounded part of the blade.

$$S_h = \frac{f \cdot l}{w_s} \tag{1}$$

3. The results of the experiment

In the experiment [7] is described that the main difference between a cylinder and the tested blade is that the aerodynamic noise of the blade is higher than from a cylinder. The noise generated from cylinder is not depended on material of the cylinder. The noise generated by the blade contains discrete audible tones. This may be caused by vortices being created behind the blade or by the vibration of the blades surface. The profile of the blade is not so aerodynamically optimal, particularly the transformation from the rounded edge to the flat surface, see figure 1.

The most of peak values of Strouhal number in the relative spectrum are for the angle 0°, in the position D, which is the noisiest. Figure 3 shows the comparison of relative spectra of the noise, vibration and fluctuation of the blade at position D (rounded edge against the flow).

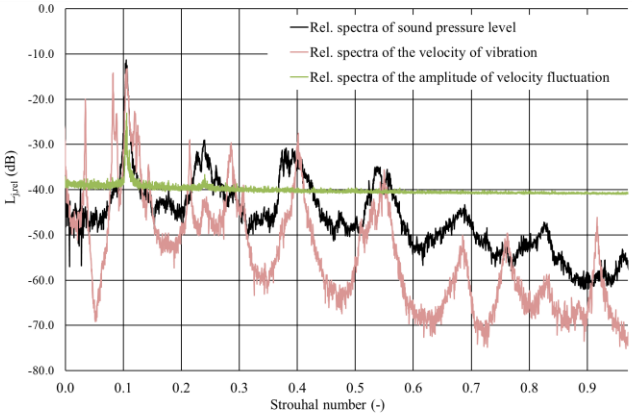

Fig. 3. *Position of the blade D – rounded edge against the flow velocity 12 m/s, The relative spectrum of sound pressure level at a distance 1 m (black colour), velocity of blades vibration (red colour) and velocity fluctuation of turbulent flow 30 mm behind the blade (green colour).*

The dominant peak value of Strouhal number for position D is S = 0.11 (approx. 400 Hz). For this value is a significant similarity of the spectra of noise (the peak value is 28 dB), vibration (peak value is 138 mm/s) and fluctuation of turbulent flow. The next one significant similarity of the peak of Strouhal number is S = 0.24 (approx. 800 Hz) which is the natural multiple of the first peak. The emitted noise spectrum (black colour) has a peak value with the natural multiple of the first significant peak where the other spectra are very similar. The spectrum of the velocity of vibration (red colour) has many peaks under S = 0.3 at the spectrum but only two peaks have an identity with emitted noise, others probably are not related with turbulent flow (fluctuation of velocity, green colour). The peaks of vibration are very similar with emitted noise for higher Strouhal number S = 0.4 (f ≈ 1290 Hz) and 0.55 (f ≈ 1740 Hz), which can be natural multiples of first peaks.

The spectra of the position H (thin edge against the flow) does not have many peaks value of Strouhal number as position D (rounded edge against the flow) although it should seem that thin edge against the flow should be worse position, because it is similar as a cylinder which has significant peak at the spectrum of the noise [4, 7]. The spectra of noise and vibration of the position H are not similar as the position D, see figure 4. The peak of velocity fluctuation (green colour) is only one around S = 0.3 (f ≈ 770 Hz) which correlate with peak of the noise spectra (black colour). The spectra of vibration correlate with the spectra of noise only for some peaks (S = 0.28, 0.47), but these peaks are not so significant as for position D. The value of noise spectra is not valid under S = 0.05 because the aerodynamic noise generated by flow around the blade is negligible for low frequencies and after correction of background noise (the noise of the nozzle) the result is not defined.

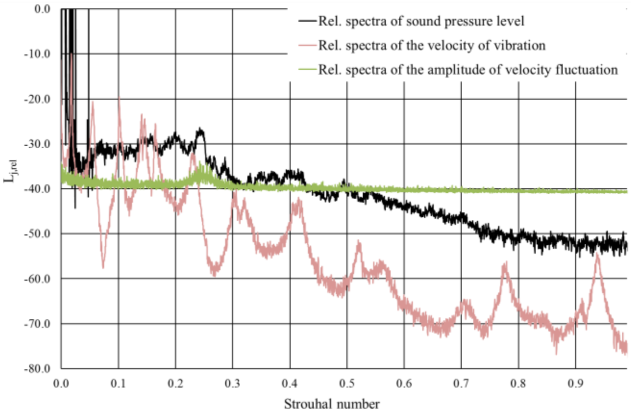

Fig. 4. *Position of the blade H – rounded edge against the flow velocity 12 m/s, The relative spectrum of sound pressure level at a distance 1 m (black colour), velocity of blades vibration (red colour) and velocity fluctuation of turbulent flow 30 mm behind the blade (green colour).*

The velocity fluctuations are more intensive for position D of the blade (rounded edge against the flow) and emitted noise is also larger than for positon H. On the figure 5 is 3D diagram of dependence amplitude of velocity fluctuation and Strouhal number for position 30 mm behind the blade in the section 40 mm with step 1 mm (in total 41 records for every measurement). The rounded edge creates the intensive vorticity which are not damped by flat parts of blade, instead the flat part of the blade works as a resonator which can generate discrete tones by vibration. The position H of the blade, see figure 6 for 3D diagram of fluctuation, does not create intensive vorticity behind the blade and vibration also does not correlate with the spectra of fluctuation as for positon D.

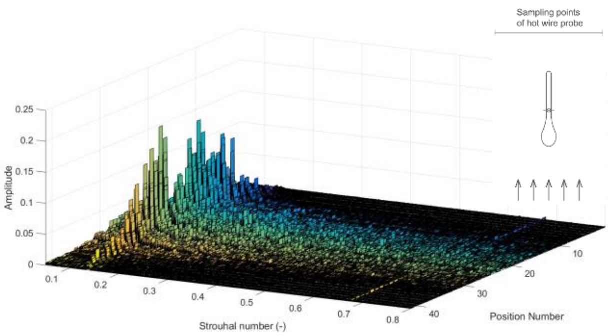

Fig. 5. *3D diagram (position of probe, Strouhal number and amplitude) for the position of blade D, airflow velocity 12 m/s.*

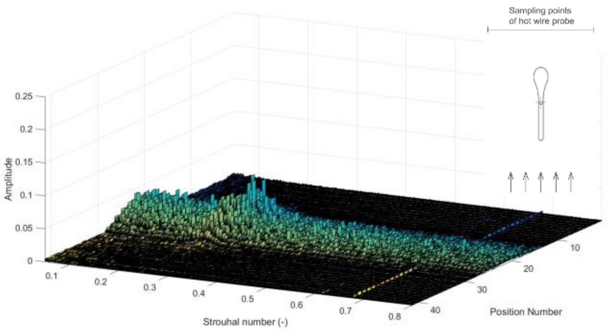

Fig. 6. *3D diagram (position of probe, Strouhal number and amplitude) for the position of blade H, airflow velocity 12 m/s.*

4. Conclusion

The tested blades commonly used in HVAC system have discrete tones for position D (rounded edge against the flow) which are natural multiples of first intensive peaks for Strouhal number 0.1. There is also significant correlation between spectra of noise, vibration and fluctuation of the turbulent flow. The source of sound or vibration of the blade surface is turbulent flow around the blade and behind the blade, specifically intensive vorticity which are generated by shape of the blade. This is caused by the unappropriated aerodynamic shape of the blade, particularly the transformation from the rounded edge to the flat surface. The emitted noise is probably created only by vorticity although the velocity vibration of the blade is approximately 138 mm/s for that specific peak S = 0.11, and that is enough. But it does not mean that it emits discrete tones of the noise spectrum although it depends on natural frequencies of the blade and also on sound emission factor. The blade has low weight (about 50 g) and aluminium is the material of the blades construction. That means the blade is pliable of the dynamic stress by turbulent flow and large value of the velocity of vibration does not necessarily mean generated the noise.

The next position H (sharp edge against the flow) does not have many peaks at acoustic spectra and vibration does not correlate with the noise spectra and fluctuation spectra as in position D.

The previous experiments for one and ten blades [5,6,7] have performed that there are three peaks of Strouhal number in acoustic spectra for low velocity of air flow (under 8 m/s), and only one peak for higher velocity, within the Strouhal number range of 0.15 to 0.25 (similarly as the cylinder). The total aerodynamic noise of blades is marginal for low speed, but the discrete tones generated mainly at low speed of airflow have a negative impact particularly in spaces as residential building or spaces with high acoustic demands as TV or recording studios.

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Nomenclature

L	the total level of the sound pressure level, the velocity of vibration or the amplitude of velocity fluctuation (dB)
L_j	the level for j-frequency of the sound pressure level, the velocity of vibration or the amplitude of velocity fluctuation (dB)
$L_{j,rel}$	the relative level for j-frequency of the sound pressure level, the velocity of vibration or the amplitude of velocity fluctuation (dB)
S	Strouhal number (-)
f	frequency (Hz)
l	characteristic dimension – thickness of the rounded edge of the blade (m)
w_s	airflow velocity (m·s^{-1})

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