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AERODYNAMIC NOISE OF BLADE GRILL HVAC SYSTEMS AT LOW MACH NUMBERS

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The paper deals with aerodynamic noise which is generated at low Mach and Reynolds numbers, by air flowing 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 in residential buildings, office buildings, hospitals and especially in spaces with high acoustic demands such as TV or recording studios. It has been experimentally assessed for a blade grill and a cylinder, in order to find similarities between their acoustic spectra. The main challenge of the experiment was to build an experimental test stand with a requirement of low noise from the fan. The goal of the paper was to compare acoustic spectra of the air flow around the cylinder, as the reference aerodynamic source, and the blade grill, as the source which generates noise by vibrations of the blade surface and by turbulent flow. The final step was to measure the fluctuations by hot wire anemometry and compare the spectra of turbulent flow fluctuations and aerodynamic noise. The air flow around the cylinder generates a peak of acoustic spectrum within the Strouhal number range of 0.15 to 0.2, which is not dependent on the material of the cylinder. This result is commonly presented in publications and has been verified by previous experiments. However, it has been found that the air flow around the blade grill generates many 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.

Keywords: blade grill, HVAC, aerodynamic noise, Strouhal number

1. Introduction

The paper deals with aerodynamic noise generated by flow at low Mach numbers around the blade grill commonly used as a terminal diffuser on air-distribution systems. The flow velocity is up to 18 m/s (under M = 0.053). This paper is part of wider research into aerodynamic noise and it is one of the first steps to obtain a deeper knowledge of the issue. The wider research is based mainly on experiments but also computational simulations are an important part [1]. They are used to obtain a better profile of the blade grill for low emission of aerodynamic noise than could be obtained experimentally.

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. This paper deals with the blade grill as the terminal diffuser. 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 airflow. For low Mach numbers it is possible to use Reynolds decompositions as a description of turbulent flow (for higher velocity it is appropriate to use Favre decompositions [2]). 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 [3, 4]. The other source of sound could be from vibrations of the blade or the cylinder 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 [5], 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 [6,7,8]. A different issue is the noise generated by a blade, see Figure 2. 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 decrease 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 vibrations of its surface was performed by Chou [9].

2. The experimental test stand

The experiment was performed on the experimental test stand. The airflow was generated by a centrifugal fan dampened by an absorption buffer for middle and high frequencies and an absorption chamber for low frequencies of noise. 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 1 for the diagram of the experimental test stand. The maximum airflow velocity in the nozzle was 26 m/s and the velocity profile was uniform. The tested object (cylinder or 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 sound pressure level was measured 1 m from the experimental subject, at an angle of 45°, in eight positions around the centre of the nozzle. The logarithmic average was calculated from the measured values. There was a direct acoustic field from frequencies of 80 Hz without a reflected sound pressure level up to the distance of 1 m from the centre of the nozzle. The sound pressure level was evaluated in centre frequency of 1/3-octave band, which was corrected for background noise caused by the nozzle. The final 1/3-octave band spectrum of sound pressure level of aerodynamic noise is considered from 100 Hz, because the noise generated by flow around the cylinder or 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 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 a 1D probe of 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 cylinder or blade in a 40 mm the section with 1 mm steps (in total 41 records for every measurement), as presented in Figure 2. 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 – 5,000 Hz), which was converted to a Strouhal number.

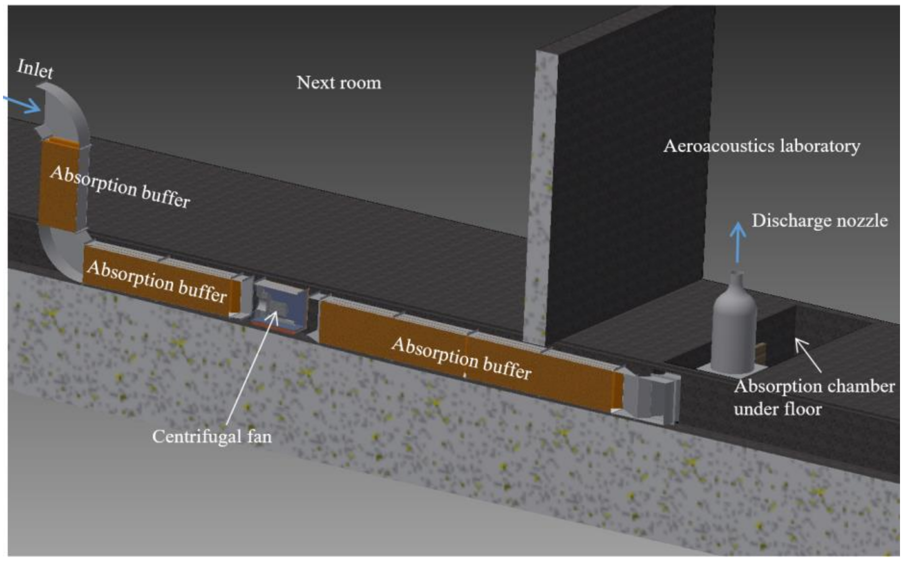

Figure 1: The cross-section of the experimental test stand.

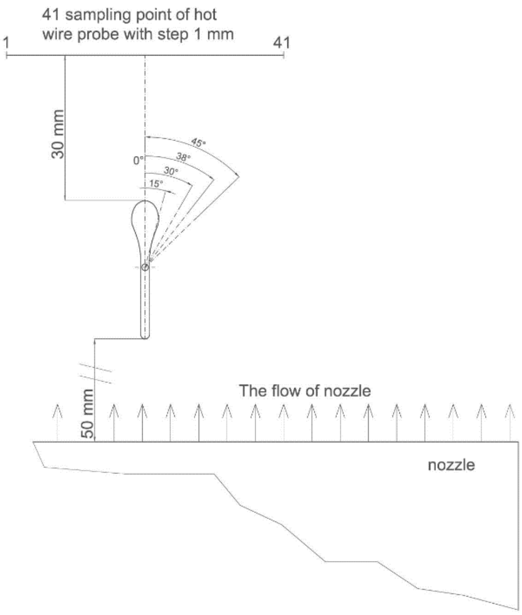

Figure 2: The cross-section of the hot wire anemometry at a distance 30 mm above the blade, this position of the blade is marked H.

The experiments were performed with one blade and one cylinder and with 10 blades and 10 cylinders situated in an aluminium frame 200 mm x 500 mm – the distance between individual blades or cylinders was 20 mm. The experiment with blades was performed in positions H (see Figure 2) and D. Position H is typical for an inlet terminal diffuser of air-distribution systems. Position D (with the rounded edge of the blade directed against the airflow) is common for an air exhaust.

3. Methodology of evaluation

The emission of noise is presented as a sound power level. The relative acoustic spectra are used as a comparison in the shape of the spectra according to the equation (1).

$$L_{Wj,rel} = L_{Wj} - L_W \tag{1}$$

where:

L_{Wj} the sound power level for 1/3 frequency band [dB];

L_W the total sound power level [dB].

The frequencies of sound or fluctuations of the turbulent flow are transformed to the dimensionless Strouhal number using equation (2). It is commonly known that for cylinders the Strouhal number has a value of between 0.18 and 0.2.

$$S = \frac{f \cdot l}{w_s} \tag{2}$$

where:

f centre frequency of 1/3-octave band [Hz];

l characteristic dimension – thickness of the blade or diameter of the cylinder [m];

w_s airflow velocity [m/s].

The measurement of aerodynamic noise of the blade and cylinder is performed for range of airflow velocities 4 – 18 m/s. The blade is evaluated for angle 0° to 45° from vertical axis, see Figure 2.

4. The results of the experiments

The experiment was performed with a blade (see Figure 2) and a cylinder diameter 4 mm. The characteristic dimension for Strouhal number was chosen the diameter of the cylinder 4 mm and the thickness of the wider part of the blade 4 mm. The comparison of the acoustic spectra of the cylinder and the blade could show the difference between generated noise. The aerodynamic noise from the blade includes discrete tones in spectra which could be caused by vibration of the blade.

4.1 The airflow around the cylinder

The experiment was performed with aluminium (mark Al) and iron (mark Fe) cylinders [8]. The different materials have different natural frequencies, so if the acoustic spectrum depends on vibrations of the cylinder's surface, there shall be a difference of acoustic spectra for the cylinder from aluminium and iron.

The resulted acoustic spectra have one peak within the Strouhal number range of 0.15 to 0.2, as expected, see Figure 3 and Figure 4. There is not a significant difference between spectra of cylinders from different materials. There is a small difference in low frequencies under Strouhal number 0.08 but that is marginal in total acoustic emission. The dominant aerodynamic noise from the cylinders is generated within the Strouhal number range of 0.15 to 0.2.

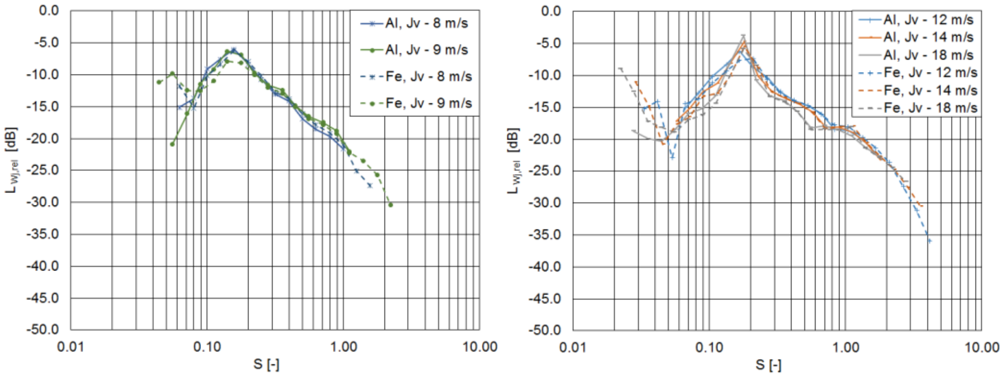

Figure 3: The relative spectrum of sound power level of one cylinder (Jv) from aluminium (Al) and iron (Fe) for airflow velocity 8 and 9 m/s (left) and 12, 14 and 18 m/s (right).

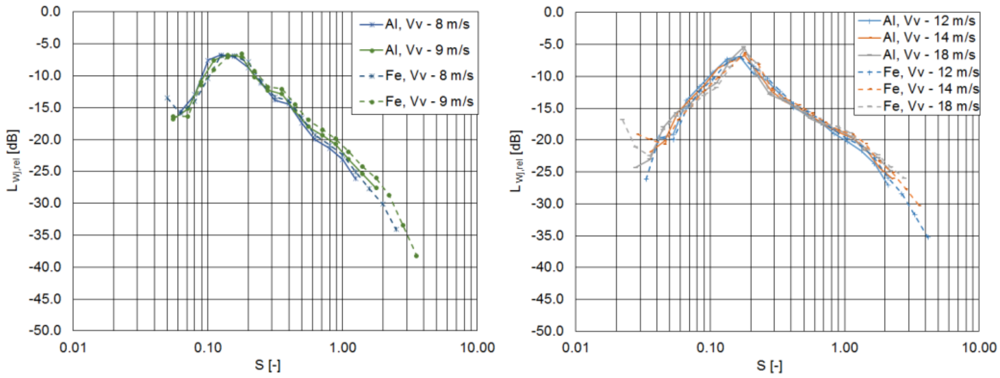

Figure 4: The relative spectrum of sound power level of ten cylinders (Vv) from aluminium (Al) and iron (Fe) for airflow velocity 8 and 9 m/s (left) and 12, 14 and 18 m/s (right).

4.2 Airflow around the blade and comparison with the cylinder

Comparison of spectra of relative sound power level of aerodynamic noise of the blade and the cylinder could show the difference between the reference aerodynamic source and object with more complicated shape. There can be expected some similarity of the relative spectra between the cylinder and the blade, e.g. the value of the peak Strouhal number is around 0.2. The comparison was performed for one blade and one cylinder in the range of the airflow velocity 4-18 m/s. The positions of the blade are marked as H, the sharp edge against the direction of the airflow, see Figure 2, and as D, rounded edge against the air flow. The angle of the blade was changed as well. The measurement was performed for the angles 0°, 15°, 30°, 38° and 45°.

The main result of the difference between cylinder and blade is that the aerodynamic noise of the blade is higher than from cylinder. The noise generated by 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.

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 5 shows the relative spectra of the blade at angle 0° and position D and H and the spectrum of the cylinder. The strongest peak is for blade in positon D within Strouhal number 0.15, the others lower peaks are around Strouhal number 0.26 and 0.4. For the higher airflow velocity at 18 m/s, position of the blade D and angle 0°, there is a dominant peak within S = 0.26 – 0.28, see Figure 6. For position of the blade H and air flow velocity 6 m/s there are the peaks for the Strouhal number 0.26 and 0.1, see Figure 5. For higher velocity the peaks are at S = 0.23 – 0.27. The cylinder has the peak within S range of 0.15 to 0.2.

For a blade at angle of 15° there is the most significant peak within Strouhal number 0.15 in the position of the blade H and airflow velocity 9 m/s, see Figure 7. For the higher velocity, there is less significant peak still within the value S = 0.15 – 0.2, similarly as for the cylinder. The situation is similar for the positions D and position H of the blade, but position D has one more peak value within S = 0.5 – 0.7.

No significant peak value in the relative spectra for higher angles (30°, 38° and 45°) was found, different situation is for 10 blades [7].

The total values of sound power levels of the aerodynamic noise of the blade corrected by filter A are impacted by peak values in acoustic spectra. The blades are the noisiest in the position D (rounded edge against the airflow) for the angle 0°, because the peaks in acoustic spectra are the most significant, see Figure 8 – dashed line. 10 blades in positions H (see Figure 8 – full line) for angle 0° are similar to 10 cylinders (see Figure 8 – dashed green line). The total sound with the blade in positions H and D is similar for the higher angles 15° (see Figure 8), 30°, 38° and 45°. The difference is up to 5 dB. The blades were louder than cylinders in every measured case. The linear dependence of L_{WA} on logarithm of the airflow velocity is with the exponent 6 – 7.5 of the velocity (see regress line in the Figure 8).

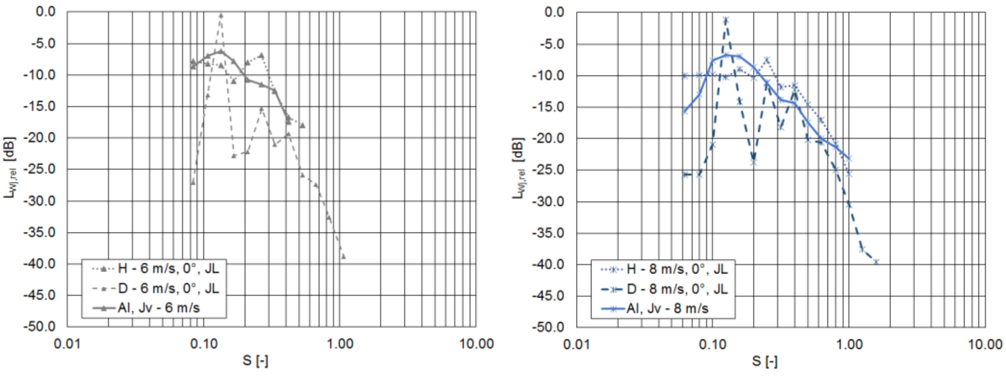

Figure 5: The relative spectrum of sound power level of the one blade for angle 0° position D (dashed line) and H (spotted line) and one cylinder (full line) for airflow velocity 6 m/s (left) and 8 m/s (right).

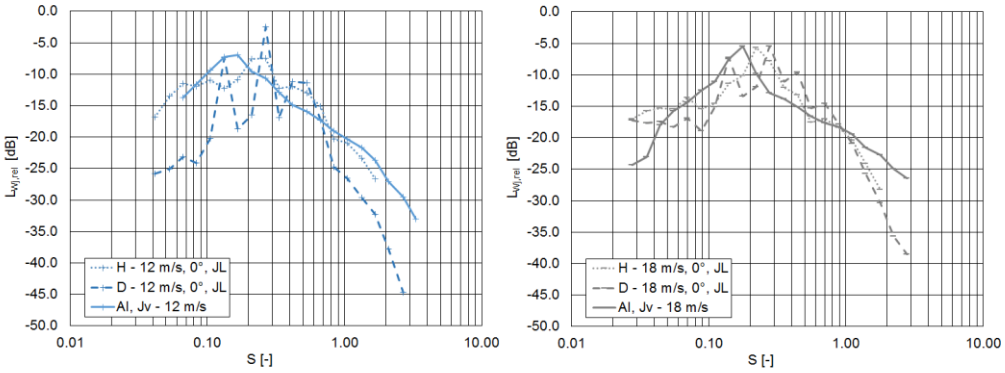

Figure 6: The relative spectrum of sound power level of the one blade for angle 0° position D (dashed line) and H (spotted line) and one cylinder (full line) for airflow velocity 12 m/s (left) and 18 m/s (right).

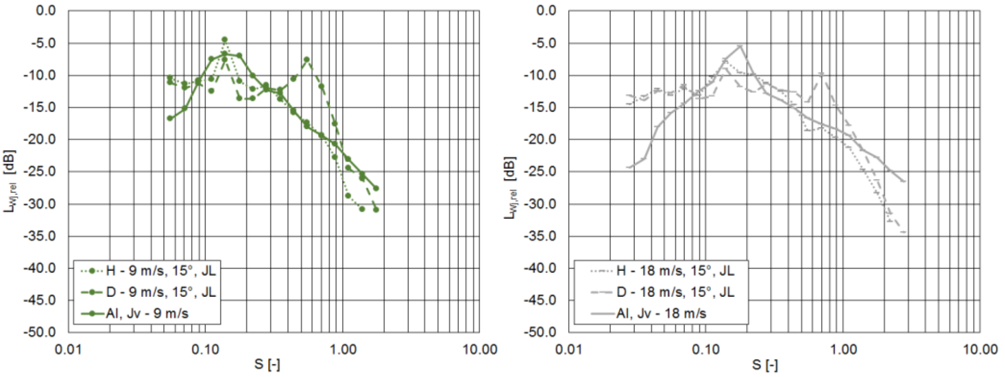

Figure 7: The relative spectrum of sound power level of the one blade for angle 15° position D (dashed line) and H (spotted line) and one cylinder (full line) for airflow velocity 9 m/s (left) and 18 m/s (right).

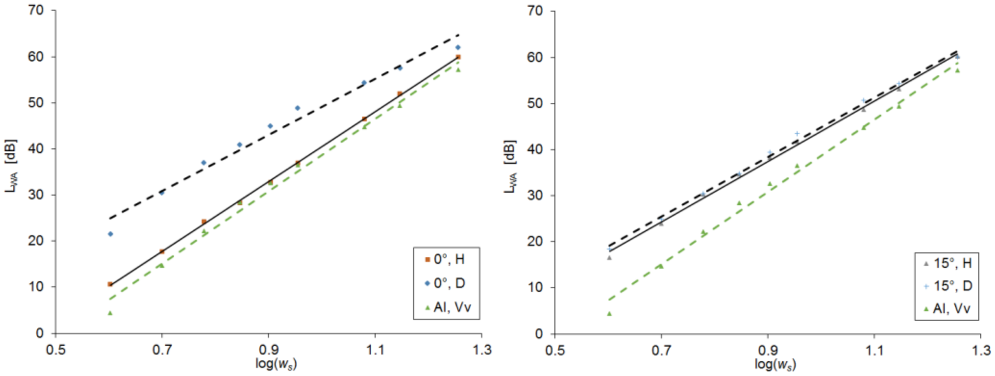

Figure 8: The total sound power level corrected by A filter dependent on log. of velocity 4-18 m/s, ten blades in the position D (dashed) and H (full) angle 0° and 15° and ten cylinders (Al, Vv, dashed green).

4.3 The evaluation of flow field behind of the blade

The stream line anemometry was used for this part of experiment, see chapter 3. The air flow velocity was measured by a 1D probe situated at a distance 30 mm downstream of the blade, see chapter 3. The peak values in aerodynamic noise spectra should correspond to the peak values of fluctuations in the turbulent flow. The spectra of fluctuations are presented for the position of the blade D, which was the noisiest (rounded edge against the flow), see the Figure 9 and 10. The peaks of Strouhal number of the fluctuations corresponds to the spectrum of the relative sound power level (see the right upper corner of Figures 9 and 10). The position of the blade D caused significant turbulence behind the blade, see comparison in Figure 11.

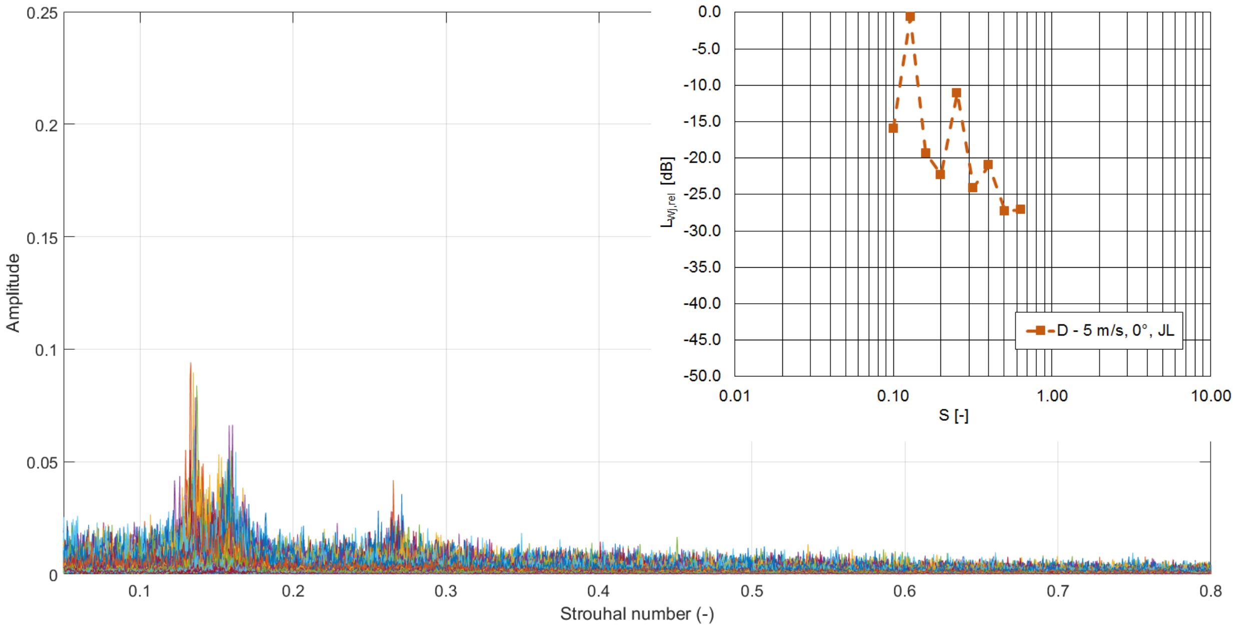

Figure 9: The amplitude of velocity fluctuation dependent on Strouhal number for the probe positions 1-41 and acoustic 1/3-octave band spectrum in the right up corner for position of the blade D and angle 0°, the airflow velocity 5 m/s.

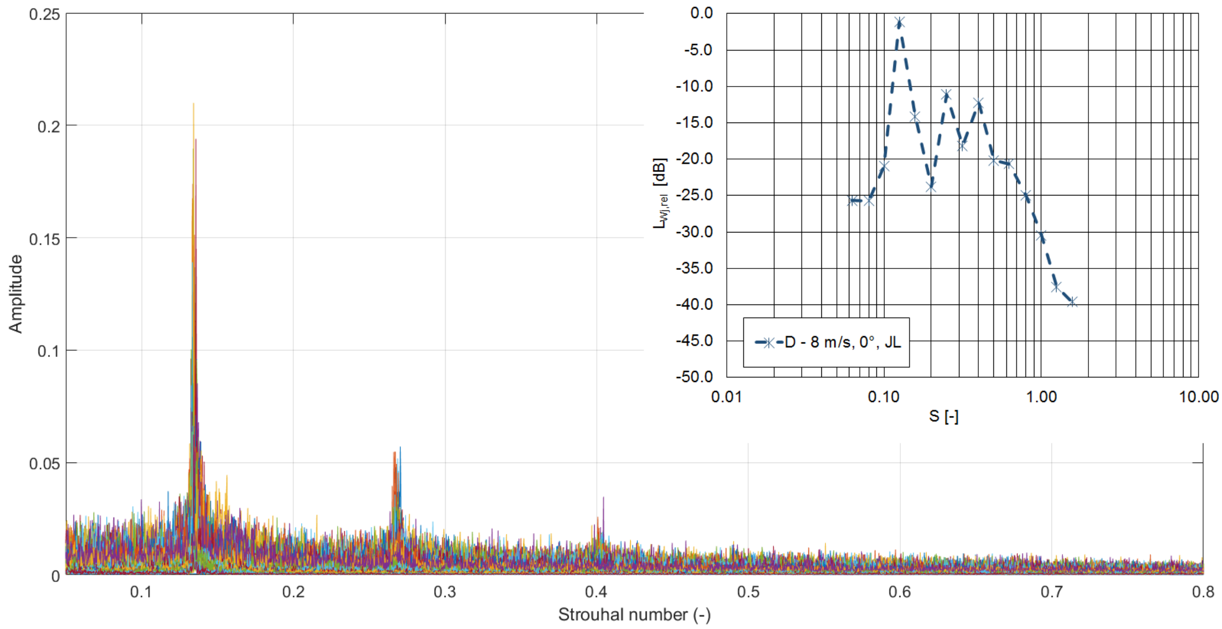

Figure 10: The amplitude of velocity fluctuation dependent on Strouhal number for the probe positions 1-41 and acoustic 1/3-octave band spectrum in the right up corner for position of the blade D and angle 0°, the airflow velocity 8 m/s.

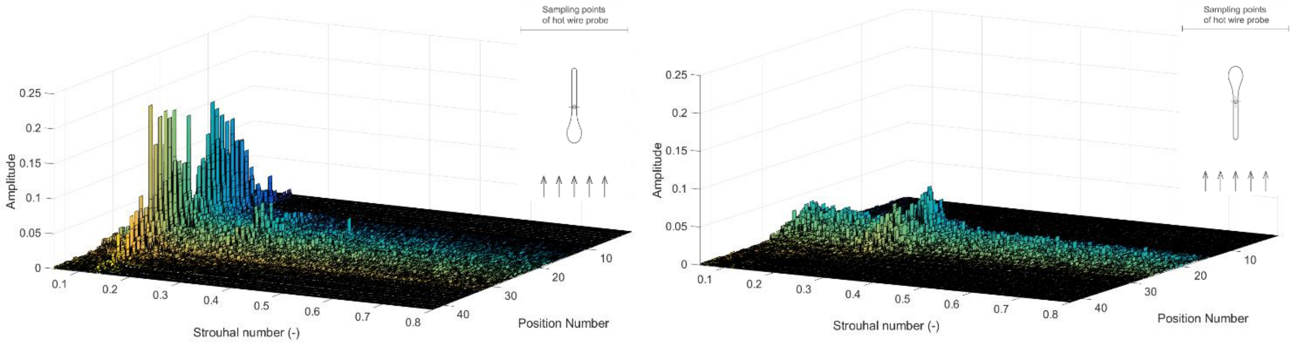

Figure 11: The comparison of 3D diagram (position of the probe, Strouhal number and amplitude) for the position of the blade – left side is D, right side is H, airflow velocity 8 m/s.

5. Conclusion

The tested blades commonly used in HVAC systems have three Strouhal number 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 (similar to the cylinder). The fluctuations of turbulent flow and probably also the vibrations of the blades generate the discrete tones at the acoustic spectra. That is caused by the inappropriate aerodynamic shape of the blade, particularly the transformation from the rounded edge to the flat surface. The total aerodynamic noise of the blades is marginal for low airflow velocity, but the discrete tones generated mainly at low airflow velocity have a negative impact, particularly in spaces with residential buildings or spaces with high acoustic demands such as TV or recording studios.

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