Comparison of slit tube probe and multi-port method for the acoustical characterisation of ducted axial fans

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ABSTRACT

In industrial applications, axial-fans are often not used as free air-intake and exhaust units, but are integrated into a duct system, especially for building ventilation. On the one hand, the installation of the fan in a duct system shifts the operating point of the fan on the characteristic curve; on the other hand, the sound spectrum emitted by the fan is also influenced. Classically, the acoustical characterisation of axial-fans in duct flows is carried out with the slit-tube-probe. On the one hand, this method does not allow the emitted sound spectrum to be decomposed according to acoustic modes, and on the other hand, it can only suppress hydrodynamic pressure fluctuations, which mask the useful signal, to a limited extent. With the so-called multi-port-method, the sound field can be decomposed into the individual duct modes by using several microphones mounted flush with the wall upstream and downstream of the fan. In this contribution, the advantages and disadvantages of the two measurement methods shall be elaborated using the example of a medium-pressure axial-fan integrated in a duct test-rig. The primary objective of this work is to derive measures for noise reduction of the overall system consisting of axial-fan and duct.

Keywords: ducted axial fan, fan acoustics, slit-tube-probe, multi-port-method

1. INTRODUCTION

The acoustical characterisation of ducted aggreagates, such as axial fans, pumps and turbocompressors, plays a major role in the industrial development of turbomachinery. Depending on the installation situation, the overall system, consisting of the unit itself and, for example, inlet and outlet duct sections, elbows, diffusers and duct terminations, emits a different sound field. Furthermore, the material of the ducts, the mounting of the entire system as well as possible expansions or constrictions of the duct diameter have an influence on the propagating sound field. The manufacturers' goal is therefore to characterise the ducted turbomachine independently of its periphery.

2. SOUND PROPAGATION IN DUCTS

Unlike in the free field, only certain modes can propagate in ducts up to certain frequencies for a given duct diameter. These critical frequencies are called cut-on frequencies and are calculated as follows [1]:

$$f_c^{m,n} = c_0 \frac{\sigma_{m,n}}{2\pi R}\sqrt{1 - Ma^2} \quad (1)$$

Here $f_c^{m,n}$, the cut-on frequency is of m.-order in the azimuthal direction and of n.-th order in the radial direction. c_0 describes the speed of sound as a function of the propagation medium and ambient temperature. $\sigma_{m,n}$ is a pre-factor derived from Bessel's differential equations as a function of the mode order. R stands for the pipe radius and, via the Mach number Ma the influence of a possibly superimposed flow velocity is taken into account. Figure 1 visualises the propagating duct modes and the corresponding cut-on frequencies for a duct diameter of 250 mm and the propagation medium air at laboratory conditions up to an upper frequency of 1795 Hz. 0/0 denotes the plane wave, which is always propagating. It must be noted that the pure azimuthal modes always occur in pairs. This means that up

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to a frequency of 1795 Hz, six modes propagate under the given circumstances.

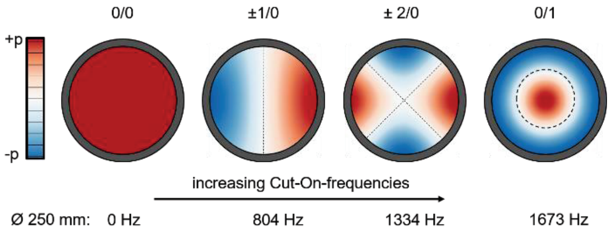

Figure 1. Mode shape of the propagating first six duct modes [2] .

Figure 2 shows the underlying physical model of acoustic mode propagation in ducts with superimposed flow. The flow profile within the duct is shown in green. In the drawing, the fan radiates sound in the area upstream (A) and downstream (B). The index + means that the sound wave p moves away from the fan. S in the diagram stands for source. The total radiated sound vector p_{A+}^{S} is composed of the superposition of the individual modes $p_{A+}^{S0,0}$ to $p_{A+}^{S0,1}$. The addition is done according to amplitude and phase.

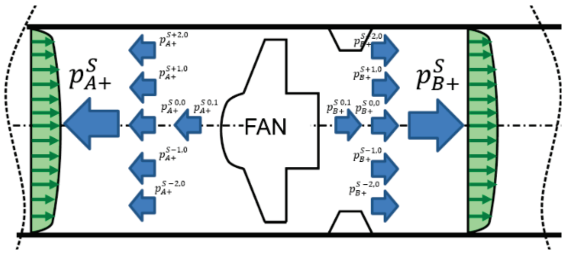

Figure 2. Sketch of the physical principle of acoustic mode superposition.

3. TEST-RIG

Figure 3 shows the test rig that was designed and built for the investigations in this document.

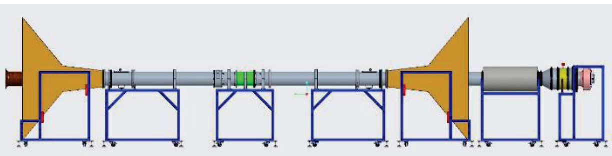

Figure 3. Test-Rig for the acoustical characterization of axial fans with duct diameters of 250 mm.

The test rig has a modular design so that most of the components can be used both for the measurements with the slit tube probe and for the application of the multi-port method. Only the duct sections in which the measurement technology is accommodated differ for the two setups. In the figure shown, the air flows through the test rig from left to right. The air is sucked into the test rig via the volume flow nozzle shown in brown in the illustration. The actual measurement section is located between the two anechoic terminations shown in ochre and is point-symmetrical. The axial fan to be examined is mounted in the middle of the test section and highlighted in green in this illustration. Behind the second anechoic termination in the direction of flow is a unit for flow conditioning consisting of an absorption silencer, a throttle unit and a centrifugal fan as an auxiliary fan. This makes it possible to set different operating points for the same rotational speed of the test fan, in other words, to run the characteristic curve.

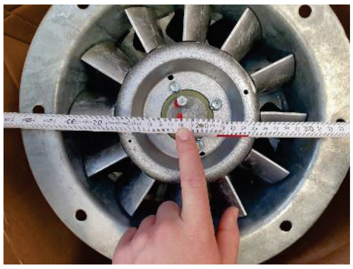

Figure 4. Photograph of the test fan.

Figure 4 shows a photo of the test fan under investigation. It is an axial medium pressure fan with a diameter of 250 mm. The fan has 12 impeller blades and also a downstream guide wheel. The present investigations were carried out at a test fan rotational speed of 3600 rpm, which corresponds to the maximum rotational speed.

4. MEASUREMENT TECHNIQUES

This section gives a brief overview of the application and post-processing of the measurement techniques used.

4.1 Slit-tube-probe measurement technique

In order to take the higher order modes into account, the standard [3] requires measurements to be carried out with the slit tube probe at not less than three points evenly distributed around the circumference. The averaged sound pressure level for the measurement with the slit tube probe is then calculated according to equation 2 as follows [3]:

$$\overline{L_p} = 10lg\left[\frac{1}{n}\sum_{i=1}^{n} 10^{0.1L_{p_i}}\right] dB + C \qquad (2)$$

$\overline{L_p}$ stands for the averaged sound pressure level per one-third octave band, n for the number of individual measurements distributed around the circumference, L_{p_i} for the sound pressure level of the i-th measurement in the respective one-third octave band and C for a correction factor specific to the one-third octave band.

Figure 5. Slit-tube-probe with probe holder and cover insert.

Figure 5 shows the slit tube probe attached to an aluminium probe holder which in turn is firmly screwed to a cover insert. This is a probe equipped with a 1/2 inch microphone.

4.2 Multi-Port measurement technique

In the following, the principle procedure for the use of the multi-port method for the acoustical characterisation of ducted axial fans will be outlined. For the sake of clarity, the description of the procedure with the help of Figures 6 and 7 is based on the acoustic two-port. Subsequently, the adaptations to the measurement set-up that are necessary in the present work in order to be able to resolve the first six duct modes upstream and downstream will be discussed.

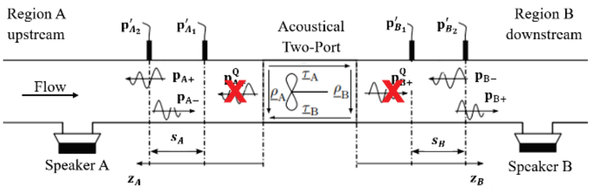

Figure 6. Principle sketch when determining the passive properties for the two-port [2].

Figure 6 shows the basic set-up for determining the passive properties, the reflection- ($\rho_{A,B}$) and transmission ($\tau_{A,B}$) coefficients, of the fan. In principle, the linear system of equations in equation 3 describes the present acoustic condition for each frequency point as follows [1]:

$$\begin{bmatrix} p_{A+} \\ p_{B+} \end{bmatrix} = \begin{bmatrix} \rho_A & \tau_B \\ \tau_A & \rho_B \end{bmatrix} * \begin{bmatrix} p_{A-} \\ p_{B-} \end{bmatrix} + \begin{bmatrix} p_{A+}^S \\ p_{B+}^S \end{bmatrix} \quad (3)$$

In a first step, speakers A and B play 106 discrete frequencies one after the other in the range between 200 Hz and 1795 Hz. Using pressure transducers, the signals are measured at the four sampling points A_1, A_2, B_1 and B_2 shown in the sketch. The loudspeaker signal must be loud enough to mask the sound emissions of the test fan. This is why the source vectors in Figure 6 are crossed out with the red x-en. Using matrix multiplications, the scatter matrix $\underline{S}$ with the passive properties can then be calculated as follows.

$$\underline{S} = \begin{bmatrix} \rho_A & \tau_B \\ \tau_A & \rho_B \end{bmatrix} = \begin{bmatrix} p_{A+} \\ p_{B+} \end{bmatrix} \begin{bmatrix} p_{A-} \\ p_{B-} \end{bmatrix}^{-1} \quad (4)$$

In a second step, the source vectors p_{A+}^S and p_{B+}^S can be determined by transforming equation system 3. For this, the loudspeakers are switched off, as shown in Figure 7, and thus the masking of the test fan is omitted.

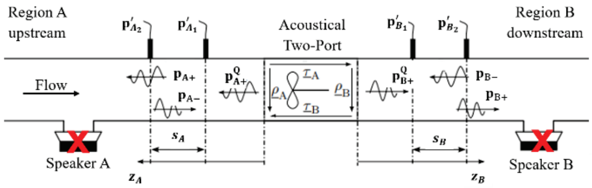

Figure 7. Principle sketch when determining the active properties for the two-port [2].

In order to expand the measurement setup in such a way that six duct modes can be resolved upstream and downstream of the test fan, some adjustments are necessary. In general, at least two pressure sensors and at least one loudspeaker are required on each side of the test object for each mode to be resolved. In the present case, this means that 6 loudspeakers and 12 pressure sensors are placed upstream and downstream respectively. The positions of the microphones were automatically optimised with the help of a genetic algorithm. Considering the 6 modes, the components in equation 3 change their dimensions as follows: p_{A+}, p_{A-}, p_{B+}, p_{B-}, p_{A+}^S and p_{A+}^S become [6x1]-vectors, $\underline{S}$ is now a [12x12]-matrix. Both the passive and active properties can now be represented separately for each mode.

5. RESULTS

This section gives a brief description of the results obtained so far for the two measurement techniques.

5.1 Slit-tube-probe

Figure 8 shows the acoustic measurement results in one-third octave band representation obtained with the slit tube probe for different operating points of the test fan. The results are averaged over the three measurements in circumferential direction (avg) and corrected with the correction factors from the standard (corr). Due to the one-third octave band representation, the peak at the blade passing frequency of 720 Hz is not as pronounced as in the narrow band representation, but is nevertheless clearly recognisable in the one-third octave band below 1000 Hz as a rise.

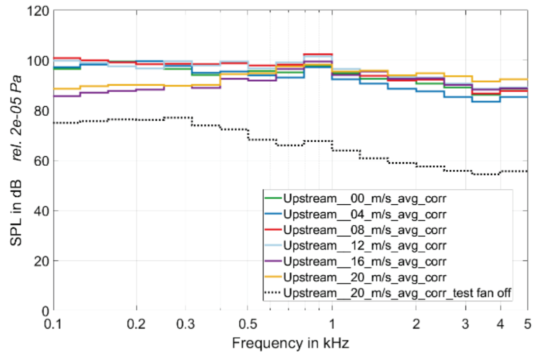

Figure 8. Slit-tube probe measurement results.

In the low-frequency range, there is initially an increase in the measured sound pressure level with increasing volume flow. From a flow velocity of 16 m/s, however, the sound pressure level in the low-frequency range decreases again.

5.2 Multi-port approach

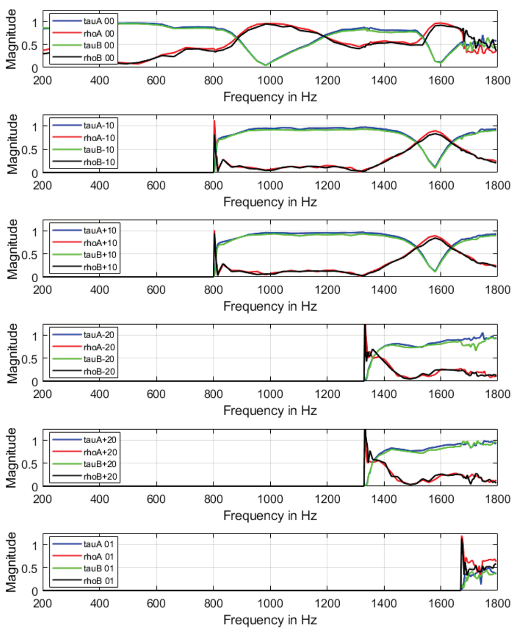

Figure 9. Passive characterization with the multi-port.

Figure 9 shows the obtained transmission and reflection coefficients for the 6 modes considered in the evaluation. In general, a value of 1 for the reflection coefficient means that 100 % of the sound energy is reflected by the fan at this discrete point. A value of 1 for the transmission coefficient means that 100 % of the sound energy is transmitted from one region (upstream/downstream) to the other. For the empty duct section, the transmission coefficient is always 1 and the reflection coefficient is always 0. The present results show that due to the geometry of the fan, strong reflections occur from the cut-on frequency of the 0.1-mode for the radial mode and the plane wave. Furthermore, with the plane wave there are strong reflections of the sound field in the range around 1000 Hz and 1600 Hz.

6. CONCLUSION

In the present work, the two measurement techniques, slit tube probe and multi-port method, were compared for the acoustical characterisation of ducted axial fans. For the investigations, a new modular test rig was built with the help of which it is possible to investigate the two measurement techniques on axial fans. The advantages and disadvantages of the two measurement techniques were discussed and first measurement results were shown. While the slit-tube probe can be used relatively quickly without major further adjustments to the test rig, the multi-port method requires extensive preparatory work with regard to sensor positioning and post-processing of the measurement data. In the future, the focus of the work will be on determining the active properties of the fan for the multi-port method.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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