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LOW FREQUENCY ACOUSTIC SOURCE CHARACTERISATION FOR IN-DUCT FANS

H. Bodén, M. Åbom

MWL, Vehicle Engineering, KTH, Teknikringen 8, S-10044, Stockholm, Sweden

Tel.: +46 8 7908021 / Fax: +46 8 7906122 / Email: hansb@fkt.kth.se

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ABSTRACT
This paper gives an overview of the field of low frequency experimental in-duct source characterisation for ventilation fans. The simplest model is the one-port model, which can be used in the plane wave region if one side of the fan is considered as fixed and the other side is duct mounted. The two-port model can be used in the plane wave region if both sides are duct mounted. The source data can be used to analyse the coupling between the ducts on either side of the fan and the characteristics of the source. The N-port model can be used either in the plane wave range if there are more than two inlet/outlet ports or it can be used for higher order modes fore a one port fan.

1 - INTRODUCTION
Acoustic source data for fluid machines are of importance for calculating the acoustic field generated in duct systems and for the design of mufflers and silencers. This information can also be used to gain a better understanding of the sound generating mechanisms in the sources, and subsequently to design machines with lower sound generation. A review of different measurement methods for determining the source data can be found in [1].
The acoustic power generated by fans is strongly influenced by various installation effects as pointed out by several authors, e.g. [2]. This fact makes measurement of the acoustical properties of fans more complex than for many other machines. All the above mentioned measurement methods are based on tests using different acoustic loads applied to the fan. There is of course a risk that this will change the source data, which are especially sensitive to changes in the inlet flow conditions. The standardised methods for rating of fans are based on determination of the sound power generated by the fan for a certain acoustic load. The only standardised in-duct measurement method to determine the sound power radiated by fans (ISO 5136) proposes the use of an anechoic termination at the ends of the duct system. This makes the measurement set-up large and quite expensive to build. It is also necessary to have several of these anechoic terminations to make measurements possible for ducts of different diameter. It is obvious that a measurement method, which does not need an anechoic termination, could make these measurements simpler and faster. Furthermore, determination of the full source data gives a much more complete source description, which can be used to calculate the sound field for any acoustic load and to design silencers taking the source-load interaction into account.

2 - ONE-PORT SOURCES

2.1 - Experimental methods for determining source data
All fluid machines, e.g. pumps, fans, internal combustion engines, etc. have at least one inlet and one outlet opening. In the case where one opening is kept unchanged, i.e., the acoustic load seen from this opening never changes, it can be treated as a part of the source. The source can then, assuming plane waves and a linear and time-invariant system, be treated as an acoustic one-port source. This model can also be used when the openings are acoustically uncoupled from each other. In the frequency domain an acoustic one-port can be completely described by a source strength and a source impedance (or a reflection coefficient). The measurement methods used to determine the source data of one-ports can be

divided into direct or external source methods and indirect or multi-load methods [1]. For fans external source methods have been used exclusively. As pointed out in [3] these methods are to be preferred when it is possible to use them. They are two-step methods. First the source impedance is determined by exciting the source with the sound field from an external source. The same type of methods used to measure the acoustic impedances of passive systems can then be used. In the second step the external source is turned off and the source strength is determined by making a pressure measurement when a known acoustic load is applied to the source.
In the frequency domain an acoustic one-port can be completely described by a source strength p_+^s and a source reflection coefficient R_s

$$p_+ = R_s p_- + p_+^s \tag{1}$$

where p_+ and p_- are the travelling pressure wave amplitudes for the plane wave in the positive/negative direction at the reference cross-section (see Figure 1). If the source auto-spectrum which formally can be defined as $G_+^s = \left|p_+^s\right|^2$ is introduced, equation (1) can be interpreted for all types of signals. In the literature the source model for 1-ports is often expressed in terms of a source strength (p^s or q^s) and a source impedance (ζ_s)

$$p = p^s - Z_o \zeta_s q \tag{2}$$

where p^s is the source pressure, p and q are acoustic pressure and volume velocity, respectively, and Z_o is the characteristic impedance of the fluid. The volume velocity q is defined positive in the outward direction from the source and all quantities are referred to a reference cross-section.

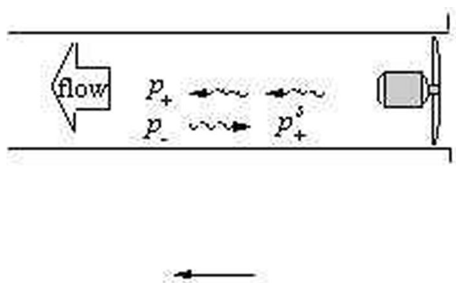

Figure 1: An in-duct source modelled as an acoustic one-port.

2.2 - Experimental results

Figure 2 shows the measured source impedance at the outlet of an axial flow fan mounted in the wall between two test rooms [4].

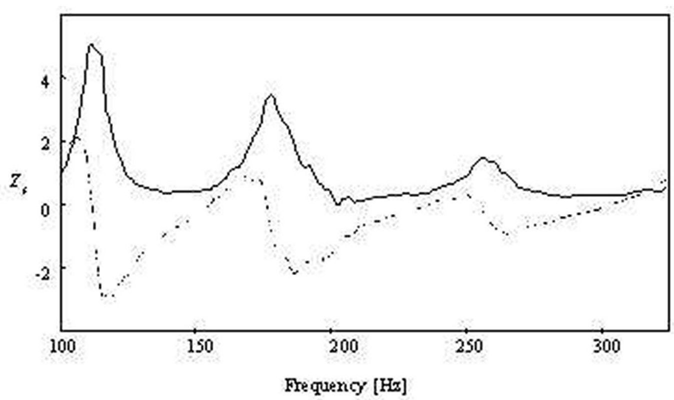

Figure 2: Normalized source impedance; continuous curve: real part; dashed curve: imaginary part.

3 - TWO-PORT SOURCES

3.1 - Experimental methods for determining source data

For fans the acoustic coupling between the inlet and the outlet and changes in the conditions on both sides

must normally be considered. The first paper on applying two-port models to fans was the review paper by Cremer [5] containing a discussion of some investigations about axial and centrifugal fans treated as active multi-ports. The first investigation of two-port sources for fans using modern instrumentation and the two-microphone method for plane wave decomposition was made by Terao and Sekine [6]. They presented a method to determine the source data of an active two-port source and used it to determine the acoustic data of a small axial fan. To suppress disturbing flow noise they suggested the use of two reference microphones located on opposite sides of the fan. However, as pointed out by Åbom *et. al.* [7] this method only works when the components of the source strength vector are completely coherent. Lavrentjev *et. al.* [8] later published a further improved measurement method for determining the two-port source data with applications to fans.
If the travelling pressure wave amplitudes p_+ and p_- are chosen as state variables the relationship between the input and the output can be expressed using a scattering-matrix form. For an active acoustic 2-port (see Figure 3) it can be written as

$$\begin{bmatrix} p_{a+} \\ p_{b+} \end{bmatrix} = \begin{bmatrix} \rho_a & \tau_a \\ \tau_b & \rho_b \end{bmatrix} \begin{bmatrix} p_{a-} \\ p_{b-} \end{bmatrix} + \begin{bmatrix} p^s_{a+} \\ p^s_{b+} \end{bmatrix} \tag{3}$$

or

$$\mathbf{p}_+ = \mathbf{S}\mathbf{p}_- + \mathbf{p}^\mathbf{S} \tag{4}$$

In order to characterise an active two-port $\mathbf{S}$ and $\mathbf{p}^{s}$ must be determined. For two-port sources direct or external source methods are used exclusively. When an external source method is used only the sound generated by this source should be picked up by the transducers in the first step of the measurement procedure. It is therefore necessary to generate an acoustic field uncorrelated with the field generated by the active two-port or which dominates over this field. By, in this way, eliminating $\mathbf{p}^s$ from equation (4) we can first determine $\mathbf{S}$ and then by turning off the external source we can determine $\mathbf{p}^{s}$ by measuring p_+ and p_-.

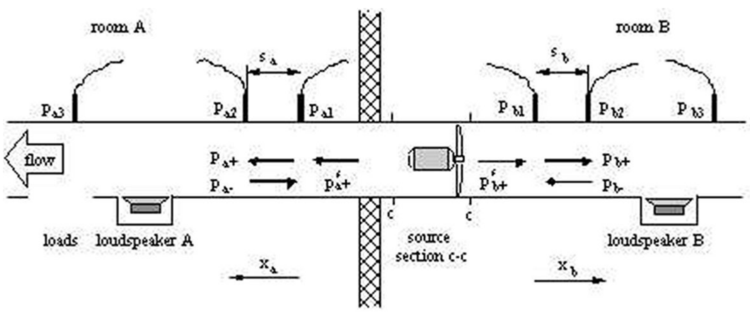

Figure 3: Test rig for two-port source measurements.

3.2 - Experimental results

Experimental tests were made on an axial flow fan in the test rig shown in Figure 3. In figure 4 a comparison between measured sound pressure level and sound pressure level predicted using the measured source data is made. As can be seen the agreement is very good.

4 - N-PORT SOURCES

4.1 - Experimental methods for determining source data

The one-port and two-port models are only valid in the plane wave range. To extend the experimental source characterisation methods to the case that a number of modes are propagating in the ducts the N-port source model has been suggested [9]. If the fan has only one opening where the acoustic state can change and if N modes are propagating in the duct coupled to this opening, it can be modelled as an acoustic N-port. An acoustical N-port can be defined as a system with N inputs and N outputs. The state at the inputs and outputs can be completely described by using N state variables. If we use the acoustic pressure amplitudes as these state variables the N-port source (see Figure 5) can in the frequency domain be described by the equation

$$\mathbf{p}_+ = \mathbf{R}^\mathbf{s}\mathbf{p}_- + \mathbf{p}^\mathbf{s}_+ \tag{5}$$

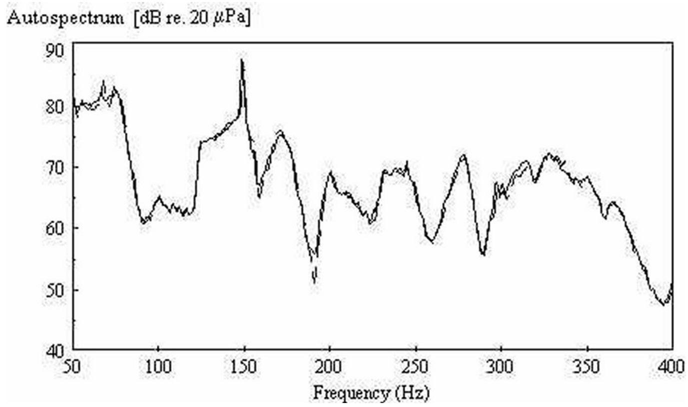

Figure 4: Comparison between the measured and calculated sound pressure levels from the fan running a 1430 r/min.

where $\mathbf{p}_+$ and $\mathbf{p}_-$ are [N ×1] vectors which contain the right - and left - going pressure wave amplitudes for N modes, $\mathbf{R}^s$ is the [N ×N] source reflection matrix and $\mathbf{p}_+^{\mathbf{s}}$ is the [N ×1] source strength vector and all quantities are referred to z=0. The easiest way to find the unknowns $\mathbf{R}^s$ and $\mathbf{p}_+^{\mathbf{s}}$ is to use an external source two-step procedure similar to the technique described for the two-port source above. First, by using an external source (e.g., a loudspeaker) which is uncorrelated to the N-port source we eliminate $\mathbf{p}_+^{\mathbf{s}}$. From a number of measurements of this type we can determine the source reflection matrix $\mathbf{R}^s$. Secondly, when $\mathbf{R}^s$ is known we can by applying a known load determine the source strength vector $\mathbf{p}_+^{\mathbf{s}}$. In order to determine the source reflection matrix, we have to obtain first the state vectors $\mathbf{p}_+$ and $\mathbf{p}_-$. For this we perform a spatial sampling of the sound field by measuring the field at 2N independent spatial positions in two cross-sections 1 and 2, see Figure 5.

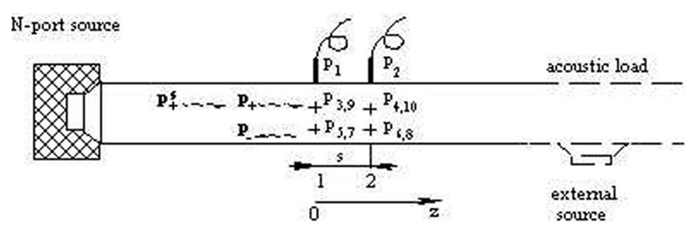

Figure 5: Experimental characterisation of acoustic N-port sources; the 2N spatial sampling points are divided equally between section 1 and 2; in the test measurement 10 points were used.

4.2 - Experimental results

Figure 6 shows the measured source strength for the plane wave and the first higher order modes and a comparison between measured and predicted sound pressure level in the duct. It can be seen that a good agreement can be obtained even after the cut-on of the first higher order modes.

5 - CONCLUSIONS

An overview of measurement methods used for low frequency source characterisation for ducted fans has been made. The models considered were the one-port model, the two-port model and the N-port model. It was found that methods exist which can produce good results. Further research is needed to develop practical methods for the mid-frequency, few mode, region. For high frequencies traditional sound power based methods work well. Further research is also needed for non-duct mounted fans and fans mounted in very short ducts.

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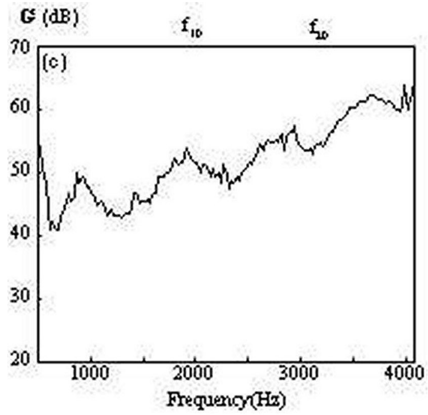

Figure 6(a): Source strength; −−−: plane wave, − − −: first higher order mode, − − −: second higher order mode.

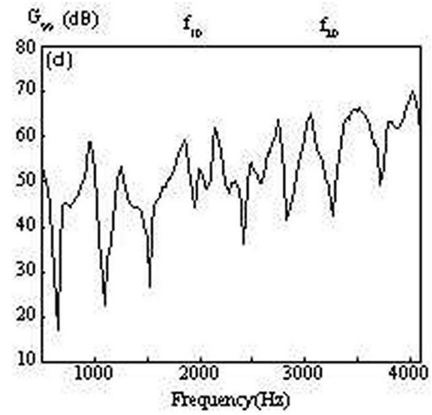

Figure 6(b): Auto-spectrum at mic. 9, −−−: measured, − − −: calculated.

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