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SIDE BRANCH RESONATOR FOR AXIAL COOLING FAN

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Abstract

Typical noise spectrum of a cooling fan consists of a broadband noise superimposed by pure tones, mostly at the fundamental and at the harmonics of the blade passing frequency. To reduce such noise several types of silencers can be used. Active noise control is an attractive up to date method, which can be used for narrow band and broadband noise control in low frequency range. With a typical secondary monopole source only a local noise reduction can be achieved. Reduction of noise propagation with a side branch resonator is well known method, which is easy to apply. With this method a significant reduction of narrowband noise propagation can be achieved. This article describes, how these two methods could be combined to achieve global noise reduction.

INTRODUCTION

Heating, Ventilation and Air Conditioning (HVAC) systems usually generate noise that consists of discrete frequencies and broadband noise. Discrete frequencies are correlated to blade passage frequency of the fan and can be easily correlated to the signal from tachometer. Broadband random noise is generated by a strong turbulent flow or stall. Aerodynamically generated broadband noise is not correlated to any other measurable signal and needs to be detected by a microphone. For controlling a propagation of the low frequency noise in the HVAC ducts an Active Noise Control (ANC) system based on the feedforward topology are usually used. Feedforward ANC system will work properly and achieve significant performance if a reference signal is delivered to the controller. A problem arises because at the reference microphone position both, the disturbance sound pressure and the acoustic control sound pressure are combined. The coupling of this acoustic wave generated from the control speaker to the reference microphone is called acoustic feedback. Acoustic feedback is source of instability. Avoiding the acoustic feedback is absolutely necessary to avoid potential instability of the control systems. Many researchers have been investigated methods of avoiding the feedback effect. The basic approach to feedback minimisation is by using unidirectional secondary sources and/or unidirectional reference microphones. Minimisation of acoustic feedback with the unidirectional secondary source is attractive because it can be used in combination with other methods for the acoustic feedback minimisation. Additional advantage of the unidirectional secondary source in ANC system is that noise is absorbed and not only reflected as in the case of monopole secondary source.

- The oldest design of the unidirectional secondary source is based on Jessels' theory [1]. It is combined from one dipole (two loudspeakers) and monopole (third loudspeaker). All three loudspeakers are placed and driven to act together like a tripolar source. An additional simple signal processing is necessary for each loudspeaker.
- Swinbanks [2] presented secondary source made from two rings of loudspeakers. They are combined conveniently to avoid radiating noise upstream from them, but cancelling the primary noise downstream. Additional simple signal processing (pure signal delay) is needed for realization of such acoustic feedback reduction.
- Jessel's theory presents a basis for more recent unidirectional JMC actuator design, which can be realized with no inter-channel delays and consequently a simpler control algorithm can be used [3]. However, digital signal processing is still needed only to achieve directivity of secondary source.

There are other ways to minimize the feedback effect. A majority of other methods use multiple sources, multiple microphones or expansively implement digital signal processing. However, even the most sophisticated digital signal processing cannot compensate for a poorly designed acoustic part of the ANC system. Problems of instability are actually transferred from the acoustical domain into the electrical and/or digital domain. Only a few studies available to us are discussing the problem of acoustical feedback reduction in acoustical domain, as for example [4,5,6].

Our work is focused on the design of unidirectional secondary source for ANC of noise generated by axial fan working close to designed pressure difference and flow. After finishing the acoustic design digital signal processing can be still implemented for frequency response equalization. Other method for feedback minimisation can be also implemented

DESIGN OF SIDE BRANCH RESONATOR WITH DIPOLE SECONDARY SOURCE

The process of combining the side branch resonator and dipole secondary source is based on simplified Swinbanks theory. He proved that by using two successive monopole sources in the duct and with additional correct signal processing a unidirectional characteristic of the pair can be achieved. The source strength of the upstream monopole at the time t is $q_1(t)$ and that of the downstream ring is q_2, then there will be zero output from the combination of the two monopole sources in the upstream direction if:

$$q_1(t) = -q_2\left(t - \frac{b}{c_0(1-M)}\right) \tag{1}$$

Where b is the spacing between two monopole sources (figure 1), c_0 is the speed of sound and M is the mach speed number of net flow. If the speed of the airflow through the duct is less then 0.5 m/s, it has practically no influence on time delay settings [10]. From equation (1) one can derive, that q_1 must have same amplitude as q_2, but be inverted and delayed relative to m_2 by:

$$\frac{b}{c_0(1-M)} \tag{2}$$

An output P in the downstream direction depends on the angular frequency according to the expression.

$$P \propto \sin\left(\frac{\omega\tau_0}{2}\right)\cos\omega\left(t - \frac{(x-b)}{c_0(1+M)} - \frac{\tau_0}{2}\right) \tag{3}$$

Where;

$$\tau_0 = \frac{2b}{c_0(1.M^2)} \tag{4}$$

A time delay should be equal to the time needed for "anti-noise" to travel to upstream ring in order to achieve unidirectional pattern, Eq.(1). To satisfy conditions from Eq.(1) and Eq.(4), two monopole sources with the same amplitude and reverse phase have to be provided. Usually this is achieved by using two sets of loudspeakers with two different amplifiers and unit for adding time delay into the signal.

The basic idea of proposed design is to use sound pressure, which is generated on the backside of the loudspeaker for acoustic feedback reduction. A part of the sound pressure wave from the front side of the loudspeaker, which is propagating upstream, is cancelled by sound pressure wave generated on the rear side of the loudspeaker. Acoustical short circuit is used for acoustic feedback reduction and side branch resonator acts like transmission line for frequency response improvement of secondary source in band pass frequency range. Swinbanks method is actually transferred into the acoustic domain. The advantage of our method is that there is no need for any additional signal processing for achieving the directionality. However, during the design of combining the side branch resonator with secondary source some parameters have to be carefully considered:

- Length of transmission line,
- damping in the side branch resonator,

- opening cross section and
- others less significant parameters.

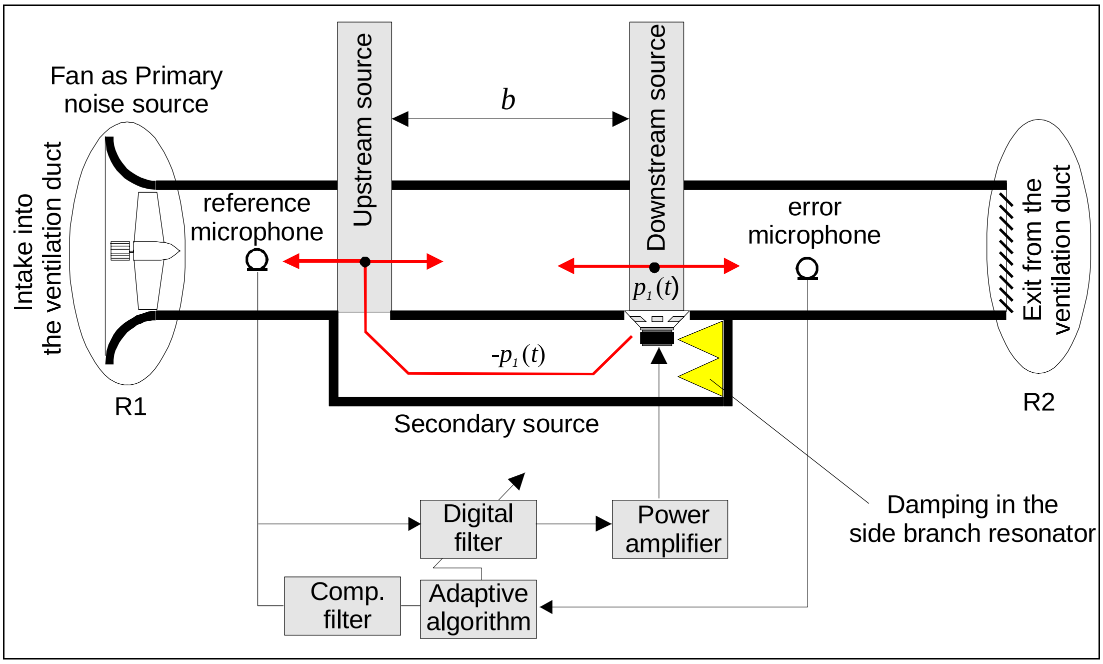

Figure 1: Side branch resonator with secondary source for ANC

RESULTS OF FEM SIMULATIONS

Inserting two simple elements (side branch resonator and dipole source), in the ventilation duct changes many different acoustic aspects of the whole HVAC system. A number of acoustical mechanisms are involved, and they all together exert an influence on the secondary source passive transmission loss and on its impulse response as active source. Some additional viewpoints are listed below:

- Due to the sudden change of impedance, at both terminations of the duct, a standing wave is formed as a result of partial reflection of sound pressure wave back into the duct. The complex reflection coefficients R1 and R2 (Fig.1) depend on frequency, duct cross-section and ventilation elements used at the duct terminations.
- Transmission loss of the side branch resonator depends on the absorption in the resonator and on its cross section.
- A real loudspeaker with complex radiation impedance acts as a resonator, attenuating noise, which is propagating through the duct.
- Due to different lengths of separated primary noise acoustical paths a linear phase difference occurs between two sound signals at summation point at the error microphone position (Herschnel-Quincke tube effect).

- Ratio between transverse dimensions to longitudinal dimension of the resonator is relatively high (0.2 m / 1m). Higher modes are analytically hard to predict (frequency range above 500 Hz in our system).

All these effects should be incorporated in the mathematical model in order to obtain accurate results. Analytical solving of this problem is not trivial. However, even an exact solution would represent only an approximation, since not all necessary parameters are known. Therefore we decided to use the Finite Element Method (FEM) for fast verification of our idea. Parameters, which are not known, were set to theoretical values or they were neglected:

- absorption coefficient of the duct walls,
- loudspeaker acoustic impedance,
- insertion loss of the loudspeaker,
- secondary source frequency response function and
- duct was discussed as infinitely long (impedance match boundary condition).

A time-harmonic analysis in the frequency domain was performed. Analysis is based on the Helmholtz equation using FEM-Lab 3.0, which is compatible with Matlab. Programing. Calculations were performed in Matlab using FEM-lab routines as Matlab functions. At discrete frequencies, a sound field was calculated and results were stored in the form of sound pressure level distribution in the duct. With successive calculations of the sound field at different discrete frequencies, a frequency response function was obtained. All calculations were performed in 2D mesh.

Length of the side branch resonator

First the influence of the side branch resonator length on the frequency response function (FRF) of the secondary source was simulated. Secondary sources FRF were simulated at the error microphone position and at reference microphone position. Duct terminations (R1 and R2) were simulated with impedance match to achieve conditions as in the infinitely long duct. Results are presented in figure 2.

FRF of systems with different length are surprisingly good at low frequency range. Such results are consequence of neglecting the loudspeaker acoustic impendence. In FEM simulations loudspeaker was simulated with surface velocity boundary conditions.

The first minimum in the FRF behaves accordingly to our expectation. Longer side branch resonator results in lower frequency of the first minimum in the FRF. Shorter side branch resonator transfers the first minimum towards higher frequency range. Consequently, shorter side branch resonator promises more flat FRF in low frequency range of secondary source. The FRF of the secondary source with short side branch resonator is lower then the FRF of the secondary source with longer side branch resonator.

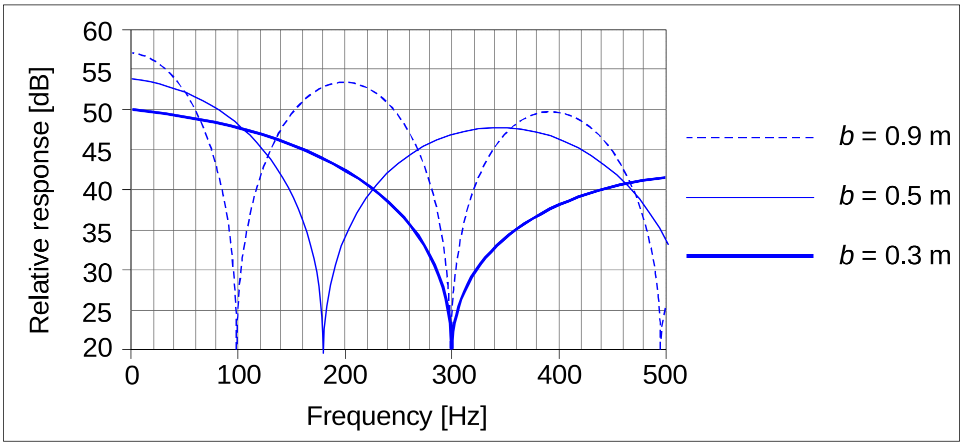

Figure 2. Frequency response of secondary source at error microphone position for three different side branch resonator lengths; b=0.9 m, b=0.5 m and b=0.3 m.

Damping in the side branch resonator

Damping in the side branch resonator significantly affects its performance to work as a reactive silencer. However, we are interested in the influence of the damping on the secondary source performance as well. Therefore four FEM simulations were performed in order to determine how a damping in a side branch resonator affects the secondary source performance for two different resonator lengths and for two typical absorption coefficients; perfect absorption and no absorption. Perfect absorption (impedance match boundary condition) can be achieved in higher frequency range above 300 Hz. In low frequency range (below 50 Hz) there is very hard to achieve significant absorption. Real system works somewhere in between.

In figures 3, a FRF of the secondary source at error microphone position (blue line) and at the reference microphone position (red line) are compared for two different damping conditions. The difference between FRF at error microphone and FRF at reference microphone presents the directional characteristic of the secondary source. Higher the difference, better the result. From results it can be concluded that unidirectional characteristics can be achieved only if significant damping is introduced in the side branch resonator. Damping also improves response of the secondary source in low frequency range below 100 Hz. If there is no damping in the side branch resonator the level of the signal from the secondary source at the reference microphone position dramatically increases. At the first minimum of the FRF the level at reference microphone exceeds the level at error microphone. Such conditions produce significant acoustic feedback and instability of ANC system.

In previous section we showed, that the length of the side branch resonator should be as short as possible. Therefore additional simulations were performed for very short side branch resonator with length *b*=0, however with the remaining geometry needed for acoustic short circuit. Results of simulation are presented in figures 4.

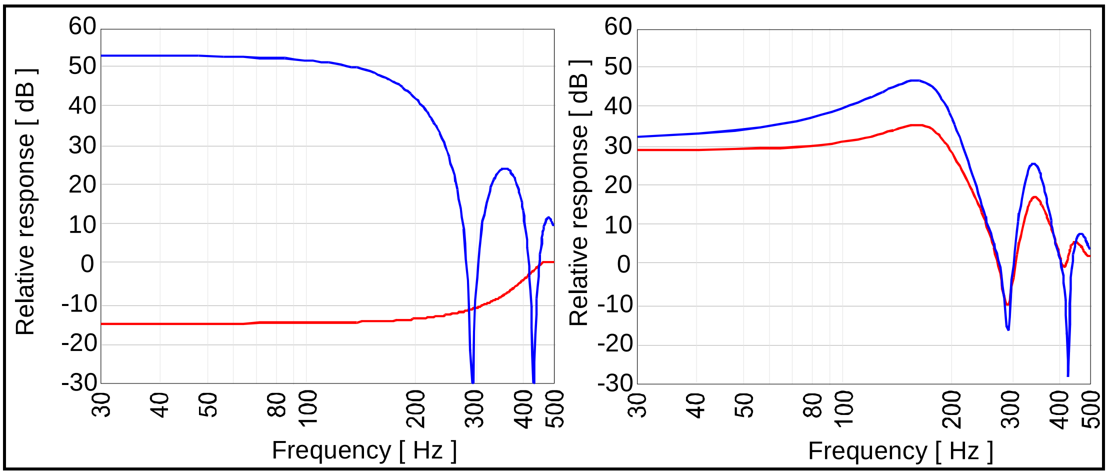

Figure 3: FRF of secondary source in 0.3 m long side branch resonator; red at reference microphone position, blue at error microphone position.
Left – perfect damping, right – NO damping

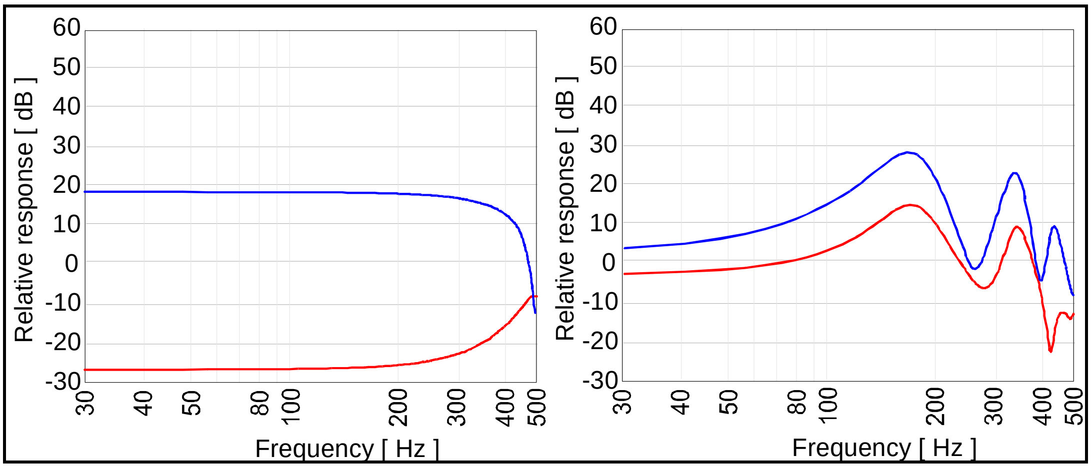

Figure 4: FRF of secondary source in 0.05 m long side branch resonator; red at reference microphone position, blue at error microphone position
Left – perfect damping, right – NO damping

A FRF of the secondary source with very short resonator and with significant damping is almost perfectly flat (figure 4 left). Sound pressure generated by the secondary source at the error microphone position (blue line) is flat and for 30 dB higher then sound pressure at the reference microphone position (red line). Only in very high frequency range (500 Hz) we can observe acoustic feedback where sound pressure from secondary source is at reference microphone higher then at the error microphone position. If there is no damping in very short side branch resonator (figure 4 right) FRF is not flat, acoustic feedback is higher and practical no useful sound pressure can be generated.

CONCLUSIONS

A dipole source was successfully implemented in a side branch resonator on the basis of the Swinbanks theory. A combination of dipole source and side branch resonator forms a secondary source for active noise control system, which is especially suitable for attenuation of fan noise. During the design process of such secondary source one has to pay special attention to proper selection of the resonator length, damping and opening cross section. Shorter side branch channel provides more flat FRF but reduces the efficiency of the system to generate sound pressure. Damping in side branch resonator should be high in order to achieve unidirectional characteristic. Proposed secondary source is designed to attenuate discrete frequencies of fan noise (BPF) as side branch resonator even if ANC system is switched off. If ANC system is switched on, the remaining aerodynamically broadband noise is attenuated with dipole source. Presented approach has three major advantages.

- Secondary source has unidirectional characteristics. Antinoise is generated only in the downstream side of the duct, minimizing the acoustic feedback effect.
- Noise transmission through the duct is reduced as the secondary source acts like reactive silencer.
- Presented secondary source is also suitable for feedback ANC configuration.

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