IMPLEMENTATION OF ACTIVE NOISE CONTROL INTO DIFFERENT FAN APPLICATIONS

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SUMMARY

This paper presents the implementation of Active Noise Control (ANC) into different HVAC fan applications. The obtained noise reduction varies considerably – in the best case the overall sound power level is reduced by about 6 dB(A) with decreasing certain frequency peaks like the blade passing frequency by up to 17 dB. In the worst case nearly no acoustic benefit by means of ANC could be found. The achievable noise reduction depends on several factors like the shape of the frequency spectrum, the coherence during the calibration process, the available installation space and the noise paths from the sound source.

INTRODUCTION

Axial and radial fans used for instance in various air conditioning systems, often are annoying due to their noise emissions. In addition to passive noise reduction methods by means of absorbing materials and mufflers, active noise control (ANC) becomes more and more apparent in the last years. Although the first patent for such a noise control system was granted to inventor Paul Lueg in 1934 already, the enhanced emergence in the recent past is due to the increasing computational capacity and speed, which is beneficial for ANC.

Conventional passive silencers produce high attenuation over a broad frequency range – from mid up to high frequencies; on the other hand, the passive silencers tend to have little impact on the noise in the lower frequency range, where the acoustic wavelength is large compared to the silencers dimensions, e.g. the length of the silencers or the thickness of the sound-absorbing material. More efficient passive low frequency silencers therefore need to be very large, which is expensive and unpractical for installation. Alternatively active silencers in combination with conventional passive absorbers can be used. The latter effects the noise spectrum in such a way that the maximum levels are in the lower frequency region up to 1000 Hz, which allow ANC to perform best.

The present paper deals with the application of ANC to different systems containing a diagonal fan of axial type with 172 mm diameter and a radial fan of 566 mm diameter. Therefore a commercial broadband feedforward ANC system (S-Cube Development Kit, Silentium Ltd. Company) is used in combination with passive noise methods on the suction side as well as on the pressure side aiming at noise reduction in these systems.

The main objective of the current investigation is to assess the possibilities and limits of the ANC technology used in fan applications. The corresponding setups, tests and measurements are mainly done in the context of two student works [1] [2].

ANC BASICS

Main parts of the ANC basics in this chapter are taken from A. Slapaks white paper "ANC Review" [3] and Hansen [6].

Introduction

The basic idea behind Active Noise Control (ANC) has been known for more then 70years. Producing an opposing signal (anti-noise) with the same amplitude as the noise you want to reduce (unwanted noise) but with the opposite phase, yields a significant reduction in the noise level (see Figure1). According to the superposition of waves, two waves with equal amplitude and identical phase have an additive effect, resulting in a doubling of the overall amplitude. On the other hand, two waves with equal amplitude but opposite phase have a subtractive effect, resulting in a decrease in the overall amplitude. If two waves are in phase, they rise and fall together but if they are exactly out of phase, one rises as the other falls and so they cancel out one another. ANC tries to eliminate sound components by adding the exact opposite sound. The level of attenuation is highly dependent on the accuracy of the system for producing the amplitude and the phase of the reductive signal (anti-noise). A comprehensive theoretical basis of ANC can be found in the literature [4] [5].

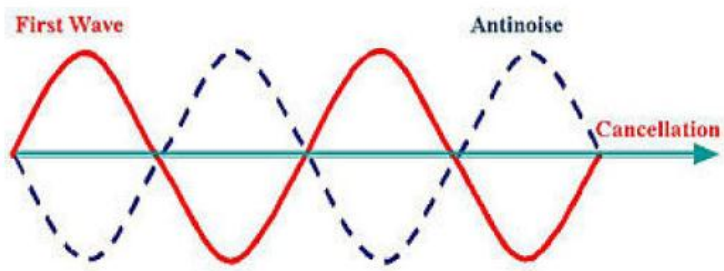

Figure 1: Superposition of unwanted noise and anti-noise

ANC System Components

According to ANC theory, there are four major components of an ANC system (see Figure 2):

1) Reference microphone: the microphone that receives the noise to be cancelled (unwanted noise) and forwards it to the controller.

2) Error microphone: the microphone that senses the noise at the point at which noise reduction is required and monitors how well the ANC system performs.

3) Loudspeaker: the device that physically does the work of producing anti-noise.

4) Controller: a signal processor (usually digital with adaptive algorithm) that tells the speaker what to do. In the simplest case, the DSP controller multiplies the reference microphone signal by minus one and sends it to the speaker to produce the anti-noise.

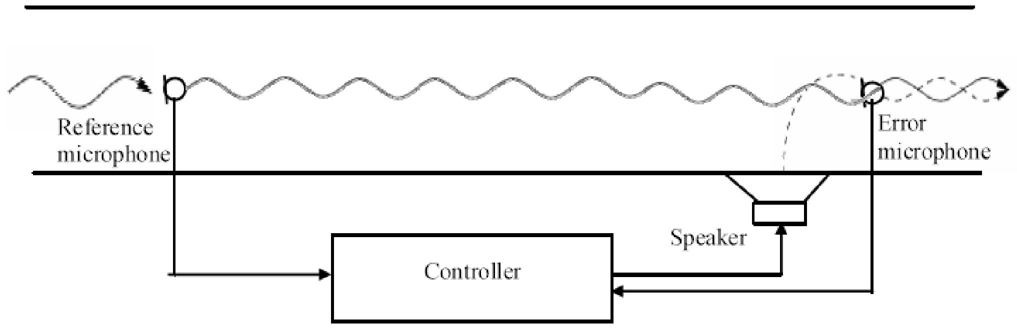

Figure 2: Typical ANC system

By detecting the unwanted noise (solid line) with the reference microphone, the ANC system can automatically generate the correct signal to send to the speaker, which will produce the anti-noise (dashed line) to cancel out the unwanted noise. The size of the quiet zone created near the error microphone depends on the wavelength of the noise. The effectiveness of the noise cancellation depends on the size and shape of the room in which the system is applied, the size of the source of the unwanted noise, the position of the speaker, the accuracy of the controller and many other parameters. Figure 3 shows the used ANC system (S-Cube Development Kit, Silentium Ltd. Company).

Figure 3: S-Cube Development Kit, Silentium Ltd. Company

Algorithms and Methods

ANC is based on the use of either feedforward control or feedback control (see Figure 4). In feedforward control, the unwanted noise signal is picked up before it propagates to the speaker. In feedback control, however, the controller attempts to attenuate the noise without the benefit of the previously described reference signal. The problem with feedforward control then is that a coherent reference signal is needed. If such a reference signal is not available, feedback control is then the alternative option. However, the control bandwidth achieved in feedback control is typically very narrow due to the nature of the speaker dynamics in the low 100-500 Hz range. The performance achieved is highly limited by the available gain and phase margins. Feedforward ANC is generally more effective than feedback ANC, especially when the feedforward system has a reference signal isolated from the anti-noise source. Most ANC systems in use and under development use feedforward control.

A useful method to avoid the need for a real error microphone in a feedforward ANC system is the virtual microphone theory, already described in the literature. This is based on a previously measured acoustic transfer function between the reference microphone and the error microphone

(MTF, see calibration process), temporarily placed at a position further away from the reference microphone and a previously measured acoustic transfer function between the reference microphone and the speaker input (STF, see calibration process). Applying the transfer function between the reference microphone and the error microphone to the reference microphone signal, yields an estimation of the source noise at the error microphone location. Applying the transfer function between the speaker input and the error microphone to the speaker input signal, yields an estimation of the reductive signal at the error microphone location. Adding the two estimated signals yields an estimation of the error signal and the microphone itself can be removed and stay virtual only.

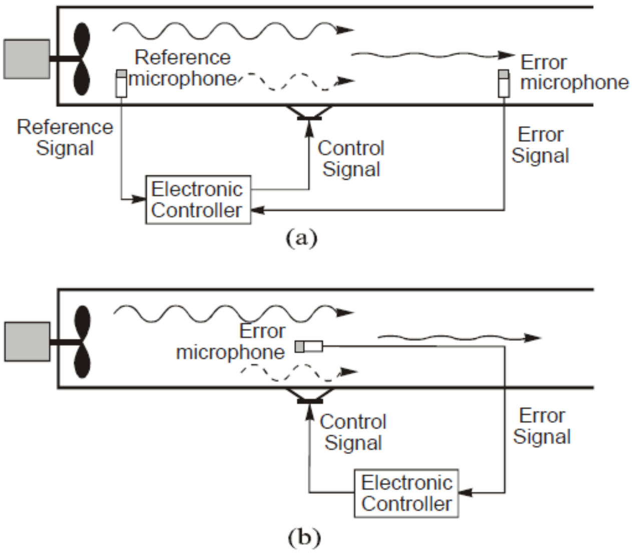

Figure 4: Feedforward (a) and Feedback (b) ANC system (from [6])

Calibration Process of the ANC System

The calibration process should be conducted in a quiet environment – background noise during the calibration influences the transfer functions and reduces the noise reduction. The reference and the error microphone should be positioned in regions with low flow velocities and should additionally be protected by windshields. The two microphones should have "eye contact", that means there shouldn't be anything in between the direct path if possible. The distance between reference microphone and loudspeaker may not be smaller than 12 cm in order that the system is able to react on the unwanted noise in real time. This minimal distance is due to dead time of electronic components like loudspeaker and DSP and the speed of sound.

The signal processing of the S-Cube DSP can be divided into four steps:

1) MTF – Microphone Transfer Function: The purpose of this step is to evaluate the transfer function between the reference microphone and the error microphone by measuring the primary noise source.

2) STF – Speaker Transfer Function: The purpose of this step is to evaluate the transfer function between the speaker and the error microphone. This is achieved by outputting a white noise signal to the speaker while the primary noise source must be off.

3) EC – Echo Cancellation: The purpose of this step is to evaluate the transfer function between the speaker and the reference microphone. The step is accomplished by outputting a white noise signal to the speaker while the primary noise source must be off.

4) PF – Prediction Filter: This filter is calculated considering the three steps above and is used to predict future sampling data from the reference microphone in order to shorten the delay of the system and to reduce the entailed size of the system.

During the calibration process, every step is performed individually for different system setups - usually repeatedly until a satisfying result is reached, which means primarily good coherence between the two microphone signals. A working speaker has limited frequency band and limited sound pressure level. If the speaker is driven with a signal that exceeds the limited frequency and intensity range, it will produce a distorted sound and in extreme cases may stop working. When the speaker produces a distorted sound the system becomes unstable and may cause increased rather than reduced noise. Therefore the system output has to be limited for some frequencies according to the speaker quality. Hence the used ANC system allows "stability adjustment" during the PF step. The calibration process is completed by a "test performance", where the noise reduction by ANC at the error microphone position is measured.

Good ANC performance results from good coherence between the two microphone signals, which often is difficult to achieve, because on the one hand the reference microphone should measure the characteristic sound, on the other hand it shouldn't be positioned directly in the flow because of flow disturbances which could affect the microphone signal.

Due to the application of the virtual microphone theory, the error microphone is only needed during the calibration process of the system, where the acoustic transfer functions are measured.

ANC IN FAN APPLICATIONS

ANC Demonstrator

The first ANC fan application described in this paper is a diagonal fan of axial type (DV6224, ebm-papst), which means, that it has a non-rotating shroud. The fan has five blades and its dimensions are 172 mm in diameter and 51 mm in axial length (see Figure 5, right). It is built in an ANC demonstrator (see Figure 5, left), which consists of a wooden box with foam coating and two spiral ducts on both sides each with a diameter of 200 mm and a length of 140mm. The ducts are also

Figure 5: ANC demonstrator (left) with diagonal fan DV6224 (right) inside

lined with sound absorbing material. The overall length of the system is 350 mm. Both suction and pressure side are equipped with an ANC system containing a circuit board in an external housing (black box on top of the ducts, see Figure 5, left), a 3-inch loudspeaker and a reference microphone positioned behind the resonance chamber. Each of this loudspeaker boxes has a cylindrical shape with a volume of 0.66 liters. This clearly breaks the rule of thumb of 0.75 - 1 liter per inch loudspeaker diameter (Silentium Ltd. Company) – but for reasons of compactness of the whole system the reduced volume is chosen.

As mentioned in the introduction active noise control should always be combined with passive noise methods. Table 1 shows the results of different configurations of the ANC demonstrator for the suction side and the pressure side separately. The installed fan is running at its best point of V = 280 m³/h with maximum speed of 3950 rpm. The operation point is adjusted by a throttle in the measurement box, where the ANC assembly is flanged to. The sound pressure levels are measured by a microphone at 1 m distance from the inlet and the outlet, respectively. The usage of absorbing materials only (wooden box and ducts) reduces the sound pressure levels of about 5 dB(A) on both sides. The additional application of ANC reduces the noise levels by further 6.4 dB(A) for the suction side and 2.3 dB(A) for the pressure side – this results in an overall noise reduction of 11.3 dB(A) and 7.0 dB(A), respectively.

Table 1: Sound pressure levels of different configurations of the ANC demonstrator, fan (DV6224) operation point (best point): V=280 m³/h, n=3950 rpm

	Suction side Lp – dB(A)	**Pressure side Lp - dB(A)**
w/o foam, ANC off	70.2	68.2
w/o foam, ANC on	67.1	68.2
with foam, ANC off	65.3	63.5
with foam, ANC on	58.9	61.2
passive noise reduction dB(A)	4.9	4.7
active noise reduction dB(A)	6.4	2.3
overall noise reduction dB(A)	**11.3**	**7.0**

Applying ANC without passive materials yields significantly worse noise reduction: 3.1 dB(A) on the suction side and no improvement on the pressure side. The reason is that the passive noise methods mainly reduce sound at frequencies above 2000 Hz, which emphasizes more the low frequency range – and this in turn is beneficial for ANC. The worse performance of ANC on the pressure side is due to the almost unavoidable flow distortion of the error microphone during the calibration process, which reduces the coherence between the two microphones.

Figure 6 depicts a comparison of the suction side FFT sound pressure spectra between ANC off (red) and ANC on (blue) at a microphone position 1 m in front of the inlet. The ANC demonstrator is arranged on a table and the fan operates at free blowing condition (V = 450 m³/h, n = 4115 rpm). It can be seen clearly that the noise reduction by ANC is very broadband up to 2000 Hz. The blade passing frequency (BPF) at f = 343 Hz and its first two harmonics is decreased by 11.7 to 17.3 dB. Figure 7 shows the corresponding diagram for the suction side 1/3-octave sound power spectra measured by 10 microphones on a surface area surrounding the inlet. The overall sound power level is reduced by 5.6 dB(A) with ANC. For the low frequencies up to 200 Hz a noise enhancement by ANC becomes apparent, which is due to a loudspeaker overload in this frequency range. It is possible to avoid this enhancement by the use of the mentioned stability filters – but that reduces the overall performance of the ANC system and is therefore not applied here.

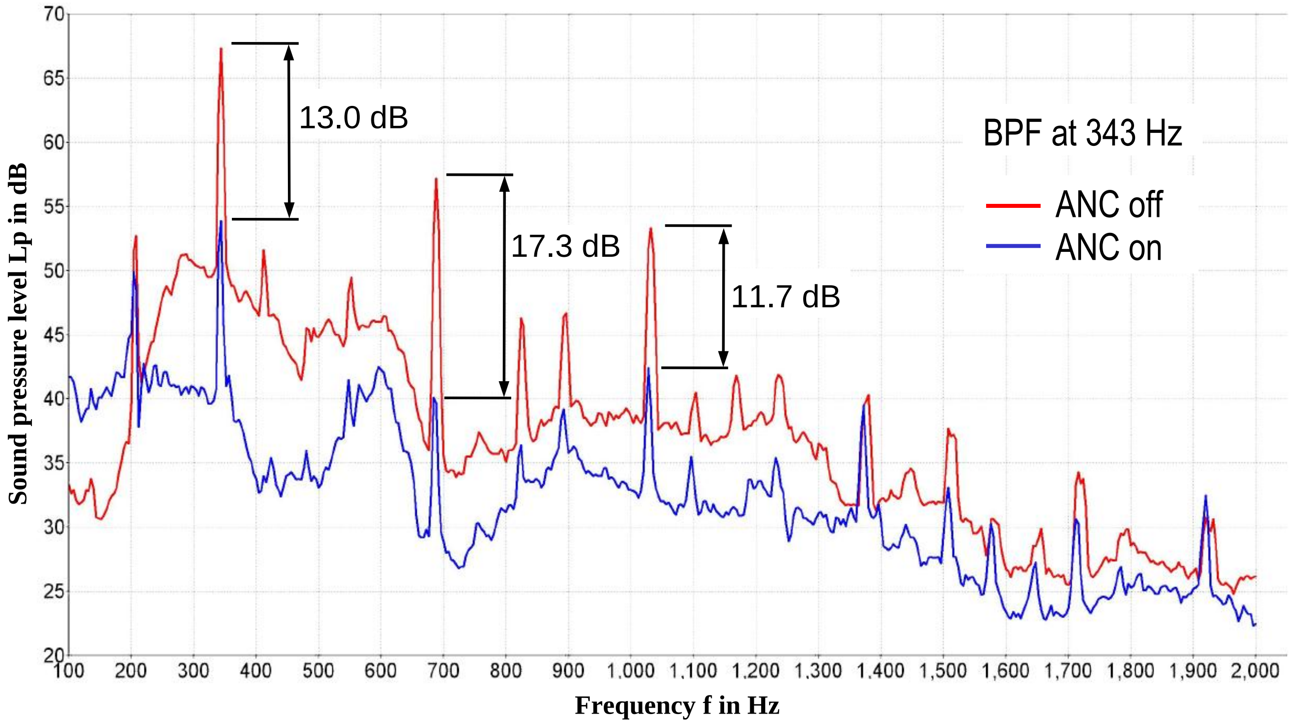

Figure 6: ANC demonstrator with DV6224 (free blowing: V=450 m³/h, n=4115 rpm): comparison of suction side FFT sound pressure spectra (taken 1m from inlet) between ANC off (red) and ANC on (blue)

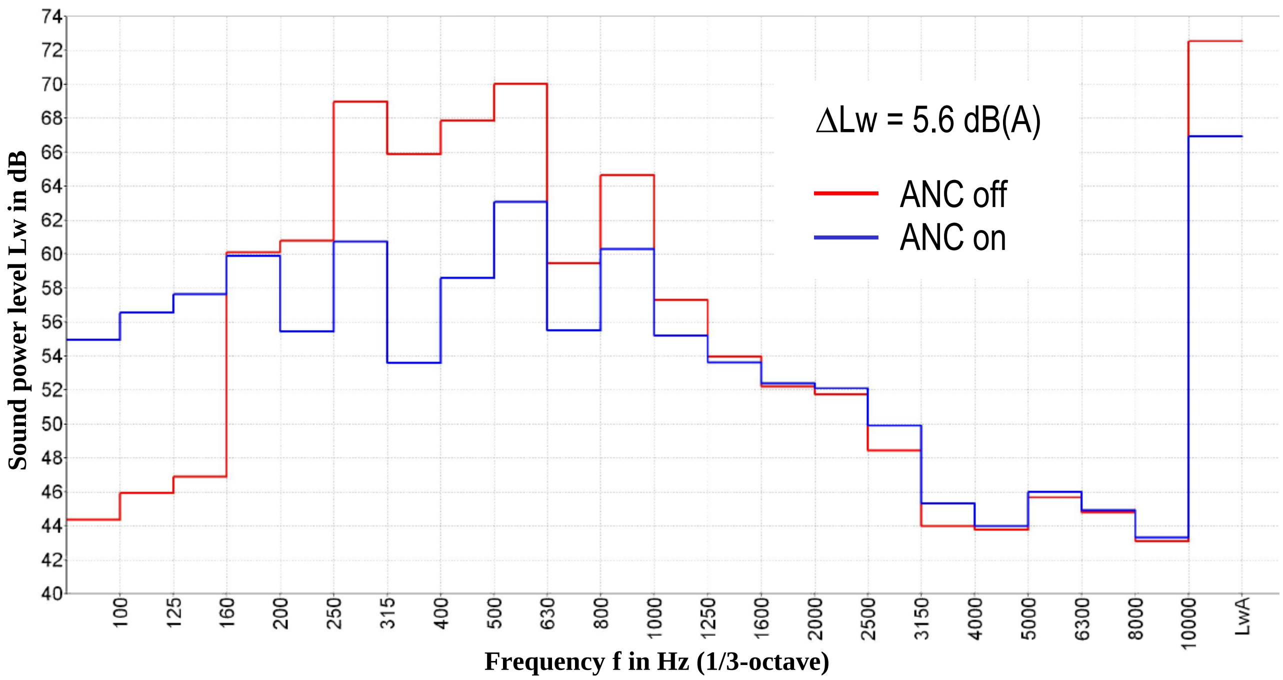

Figure 7: ANC demonstrator with DV6224 (free blowing: V=450 m³/h, n=4115 rpm): comparison of suction side 1/3-octave sound power spectra between ANC off (red) and ANC on (blue), the overall sound power levels are A-weighted

Radial Fan in HVAC Component

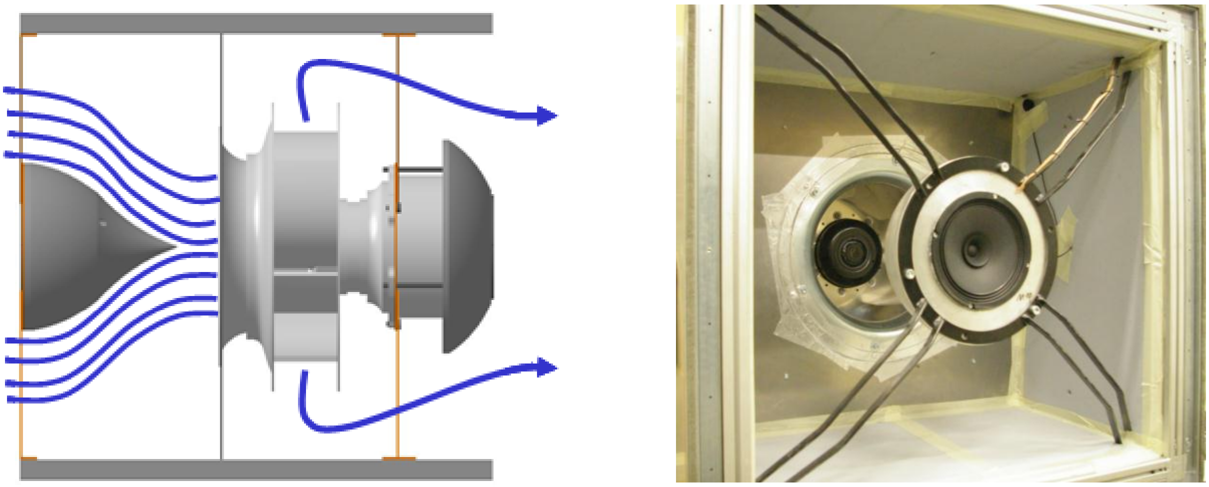

Figure 8: Sketch (left) and picture from suction side (right) of ANC application in a HVAC component with a radial fan

The second investigated ANC application is a HVAC component which is nearly cubical with an edge length of 1 meter. Figure 8 shows a sketch (left) and a picture from the suction side (right) of the component equipped with a radial fan (R3G500, ebm-papst) of 566 mm diameter and with an ANC system on suction and pressure side. On both sides 8-inch loudspeakers are installed into resonance chambers of 8 litres volume each. To improve the flow control the speaker box on the suction side is aerodynamically shaped. The additionally mounted foam coating (50 mm) at the inside of the exterior walls and the loudspeaker boxes have nearly no influence on the aerodynamic performance of the system. The whole unit considered for noise investigations consists of the described HVAC component and an additional splitter silencer with 3 baffles (length: 660 mm, width: 200 mm) attached to the suction side (see Figure 9). The 7 bladed fan is running at the duty point of $V = 8110$ m³/h and $p = 1000$ Pa with 2000 rpm. For all “ANC on” measurements shown here only the suction side ANC system was operating.

Figure 9 depicts a comparison of the sound pressure spectra at the marked error microphone position between ANC off (red) and on (blue). It reveals a reduction of 10.9 dB for the BPF at $f = 233$ Hz and 8.1 dB for its first harmonic at $f = 466$ Hz by the use of ANC. As mentioned before a good coherence between the two microphones is essential for a positive ANC performance. For the described setup this could only be reached with an error microphone position inside the unit – between the baffles and the loudspeaker. Although many different error microphone positions and two reference microphone positions (see sketch in Figure 9) were tested, no satisfying configuration with the error microphone outside the device could be found. This is recommended, because finally the noise should be reduced outside the unit, where it is annoying.

Figure 10 shows a comparison of the sound pressure spectra measured at the marked position 1 m in front of the inlet between ANC off (red) and on (blue). The BPF is decreased by about 9 dB, but in the frequency range between 300 Hz and 400 Hz there is a distinctive noise enhancement, which is probably due to a standing wave or a resonance in the system stimulated by the speaker. Furthermore Figure 10 depicts in which frequency range the splitter silencer works. It reduces noise over the whole interesting spectrum even in the low frequency range – for example at BPF of $f = 233$ Hz the level can be reduced by 17 dB.

Because no satisfying active result was reached with this setup, some other configurations without baffles were tested. The ANC performance could be improved, but on a higher overall noise level because of the missing passive means. One disadvantage of this setup is the big cross-section area.

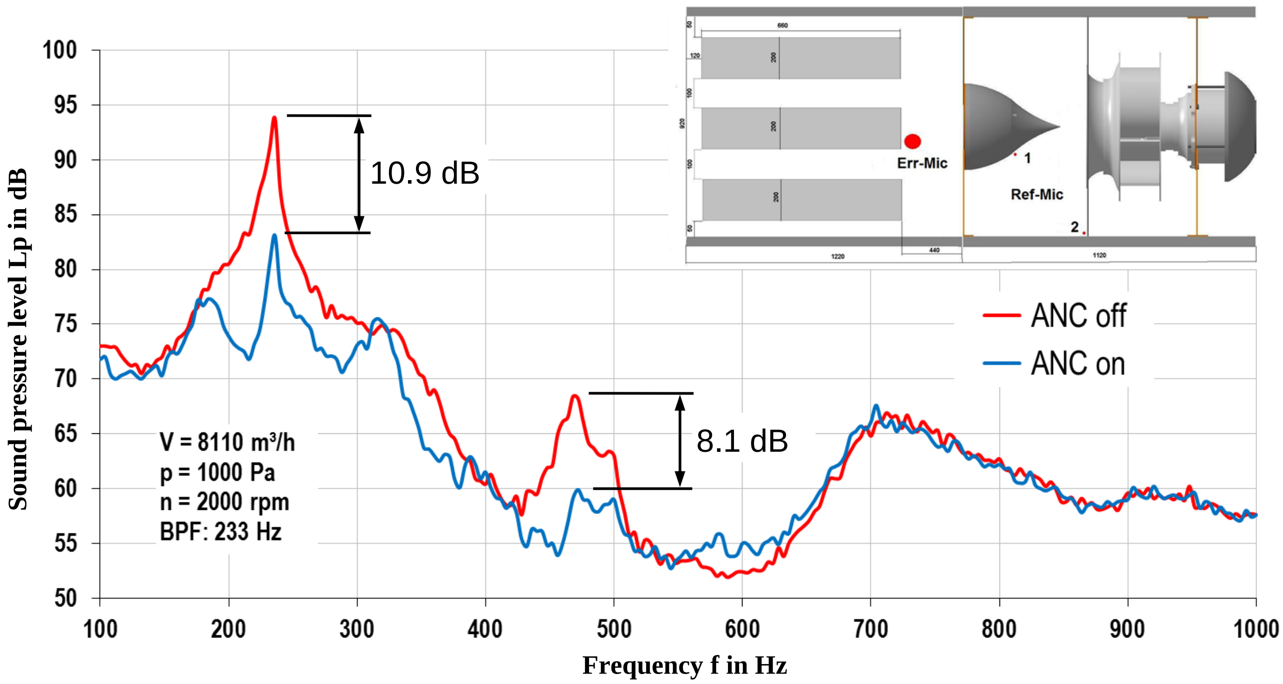

Figure 9: Comparison of sound pressure spectra at error microphone position (red dot) between ANC off (red) and on (blue), operating point at 2000 rpm

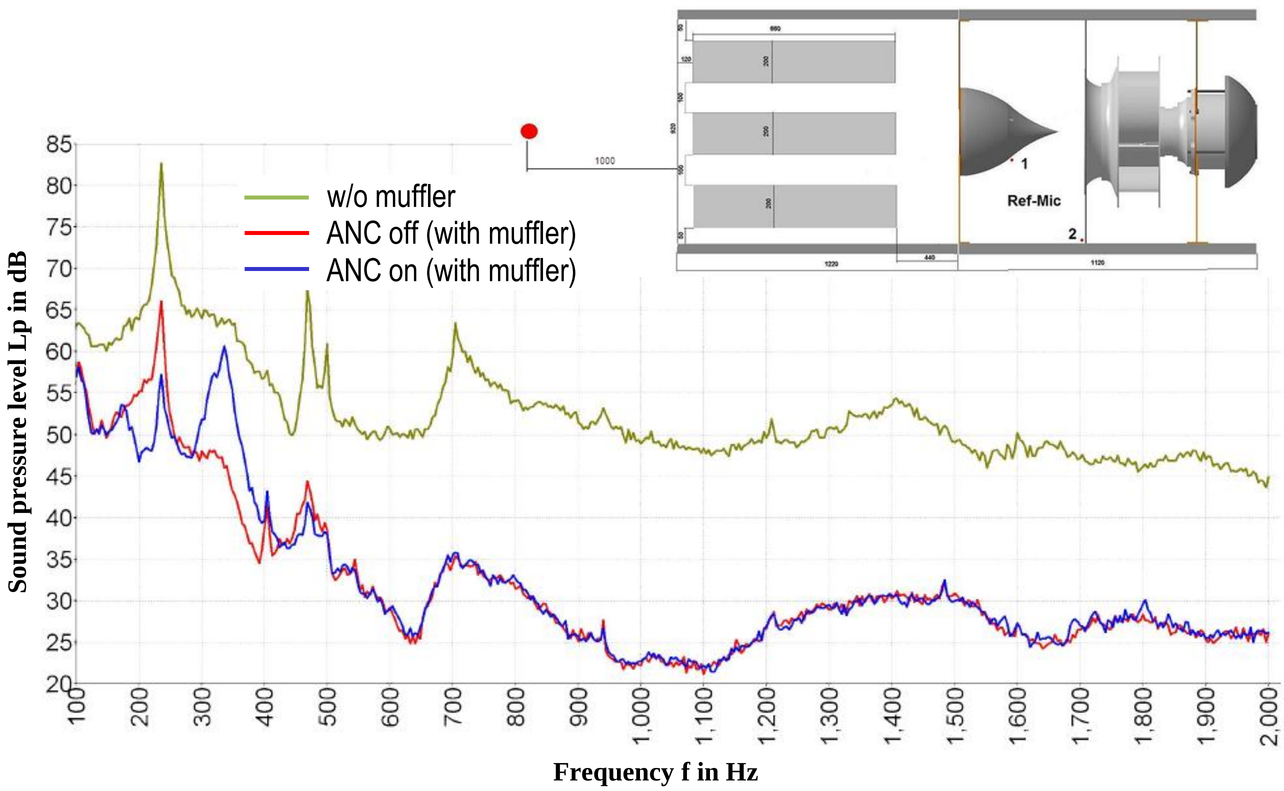

Figure 10: Comparison of sound pressure spectra (taken 1m from inlet, red dot) between ANC off (red) and on (blue), spectrum of the system without muffler (olive)

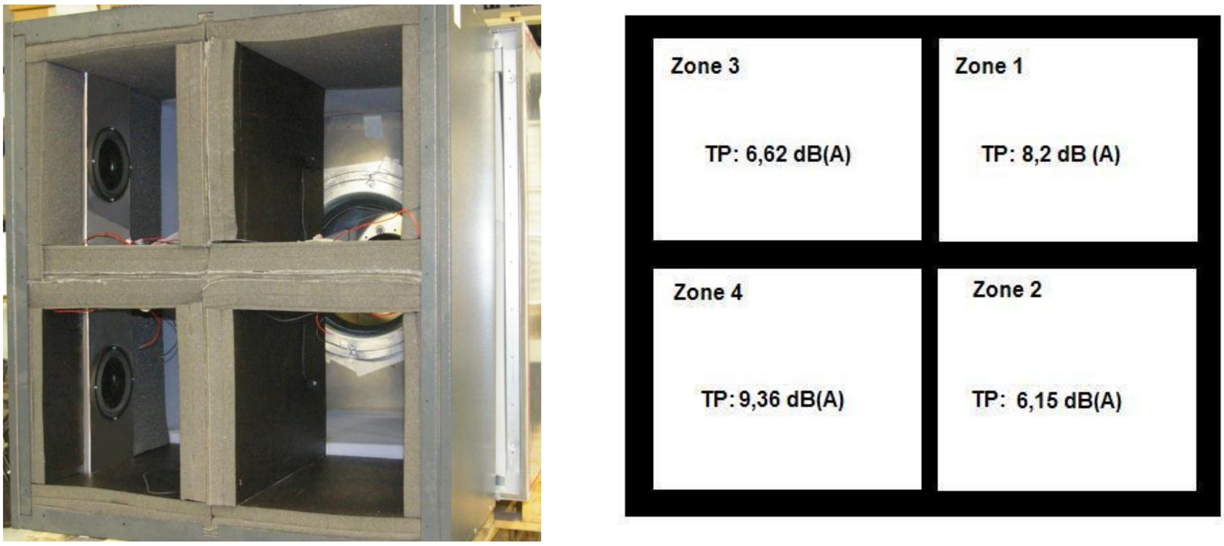

Figure 11: 4-zone-muffler with ANC equipment (left) and achieved noise reduction of single zone ANC operation at error microphone position (right)

In order to generate plane waves, which are beneficial for noise cancelling, it is recommended to divide large sound outlet areas into smaller regions. For that reason a 4-zone-muffler taken from another ANC project is attached to the HVAC unit instead of the splitter silencer (see Figure 11, left). It fits very well to the suction side dimensions of the air conditioning unit, so that only few modifications needed. The length of the muffler in flow direction is only 500 mm compared to 1220 mm of the replaced silencer – so the whole assembly is more compact. The muffler is a combined passive-active device: every zone is coated with acoustic foam and is equipped with a 6-inch loudspeaker and corresponding resonance chamber. During the calibration process the mentioned splitter silencer was mounted downstream to reduce annoying noise from the pressure side. In Figure 11 (right) the achieved noise reduction during calibration for single zone ANC operation at error microphone is stated (TP = Test Performance). That means only the respective active system of one flow channel is running and the error microphone is positioned near the inlet edge of that zone. The noise could be reduced by between 6.1 dB(A) and 9.4 dB(A).

Figure 12 depicts a comparison of the FFT sound pressure spectra measured 1 m in front of the inlet between ANC off (red) and on (blue). In the latter case all four active systems are operating. The BPF at f = 233 Hz can be reduced by 6 dB. Figure 13 shows the corresponding diagram for the suction side 1/3-octave sound power spectra measured by 10 microphones on a surface area surrounding the inlet. The overall sound power level is reduced by 2.1 dB(A) with ANC. There is little improvement potential in the mid frequency range between 1000 Hz and 1600 Hz because there an enhancement with ANC occurs.

Summing up the ANC results reached here were a little disappointing. The key issue for that seems to be the fact, that no sufficient coherence between the reference microphone and the error microphone positioned outside the unit can be obtained. Nevertheless a compact solution, which combines passive and active noise reduction methods, could be found.

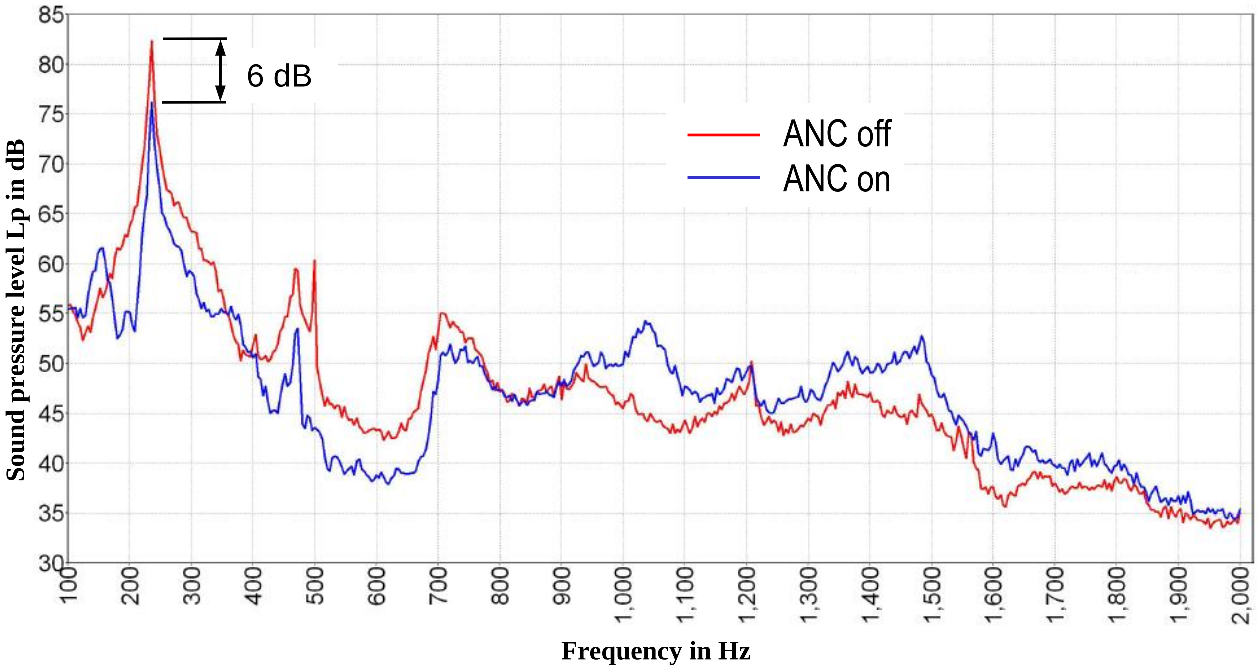

Figure 12: Comparison of FFT sound pressure spectra (taken 1m from inlet) between ANC off (red) and on (blue)

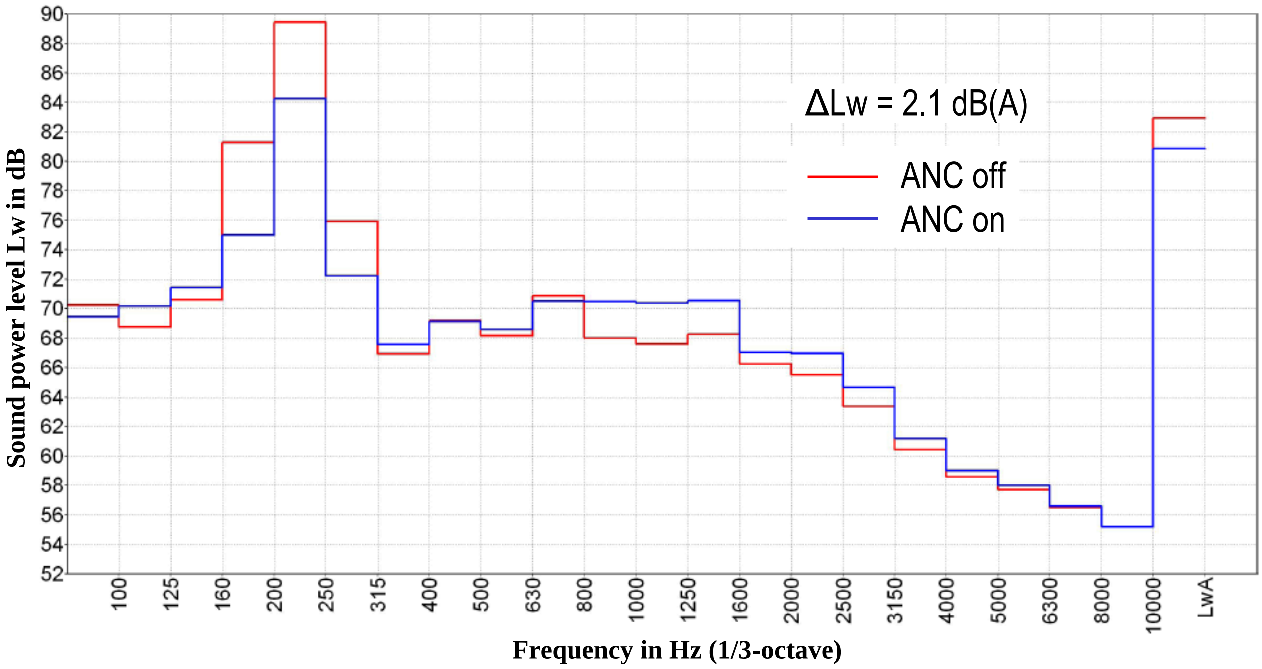

Figure 13: Comparison of 1/3-octave sound power spectra between ANC off (red) and on (blue), the overall sound power levels are A-weighted

CONCLUSIONS

The implementation of Active Noise Control (ANC) into different fan applications is investigated. The achieved noise reduction varies considerably – it depends on several factors like the shape of the frequency spectrum, the coherence during the calibration process, the available space for ANC, the installation configuration and the noise paths from the sound source.

In the best case the overall sound power level is reduced by about 6 dB(A) with decreasing certain frequency peaks like the blade passing frequency by up to 17 dB and reducing dominant 1/3-octave bands in the range of 6-10 dB. In the worst case nearly no acoustic benefit by means of ANC could be found.

For the application of ANC the noise spectrum should have maximum levels in the lower frequency region up to 1000 Hz. For an effective noise reduction a combination of passive and active acoustic means is important – especially when there are considerable components in the high frequency region. The ANC implementation should not increase the pressure loss of the system considerably, because the associated rotational speedup causes an increase of sound emission – and that reduces the potential noise reduction by the use of ANC. Of essential importance for the performance of an active system seems to be a good coherence between the reference microphone and the error microphone, which should be placed outside the assembly – at a position that characterizes the annoying sound. If this is successful, then a noise reduction not only of sound pressure at the error microphone position, but of the sound power in a larger space is possible. If an ANC system is implemented into an application it needs a certain installation space for maximum noise reduction. Often this room isn't available - so a compromise between available space and noise reduction has to be found. Eventually ANC reduces just air borne noise - structure borne noise at other locations of the device can't be reduced.

The current investigation makes a contribution to assess the possibilities of ANC technology used in fan applications. On the other hand it clarifies that there are several restrictions and limits to be considered.

BIBLIOGRAPHY

[1] P. Hollenbeck – *Geräuschreduktion bei Ventilatoren durch den Einsatz von ANC*, Diplomarbeit, ebm-papst Mulfingen GmbH & Co. KG, **2009**

[2] R. Balbach – *Active Noise Control - Geräuschreduktion bei Ventilatoren durch den Einsatz von ANC*, Praxissemesterarbeit, ebm-papst Mulfingen GmbH & Co. KG, **2010**

[3] A. Slapak – *ANC: Review*, White paper, http://www.silentium.com/UserFiles, Silentium Ltd. Company, Israel, **2007**

[4] S. J. Elliot – *Signal Processing for Active Control*, London, U.K., Academic, **2001**

[5] S. M. Kuo, D. R. Morgan – *Active noise control: systems algorithms and DSP implementations*, John Wiley and Sons Inc, **1996**

[6] C. H. Hansen – *Does Active Noise Control Have a Future?*, www.mecheng.adelaide.edu.au /anvc/publications/public_papers/2003/preprint_Hansen_Wespac.pdf, Manuscript Number: 1226U, University of Adelaide, Australia, **2003**