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Design and applications of lean active resonator silencer cassettes

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ABSTRACT

Active resonator silencer cassettes (ASCs) are composed of a housed loudspeaker coupled with a microphone sensor via an analog electronic control loop. ASC-units are very efficient in attenuating low-frequency noise, especially in applications with tight constraints on the available installation space. At the Fraunhofer IBP the design of ASC-units, ASC-arrays and their practical application has been investigated for more than two decades. This paper gives a brief overview on the characteristics, the performance and some practical applications of classical ASC-units and arrays. Classical ASC-units have dimensions in the range of decimeters. More resent work on ASCs at the Fraunhofer IBP has been focused on the design of much leaner units with dimensions in the range of centimeters. Scaling the dimensions of the ASC-units down by an order of magnitude widens the range of possible applications, but also comes with a number of design challenges. In this paper, these design challenges and the characteristics of the lean ASC-units and arrays are discussed. The paper also presents results of studies where the lean ASC-units are used to build up a compact active noise control system for a partly opened sliding window, and a compact active silencer system for a domestic ventilation duct.

Keywords: Active Noise Control, Silencer

1. INTRODUCTION

Noise pollution is an important issue in industrialized societies. Hence, noise control and sound design are an important criterion in the development of many products and installations. Most exhaust and ventilation systems comprise specifically designed silencers and/or absorbers in order to reduce noise emissions. Conventional silencers usually comprise porous absorbers and/or acoustics resonators. Porous absorbers have a broadband absorption characteristic, which mainly depends on the flow resistivity of the absorption martial. Towards low frequencies, the effectiveness of porous absorption layers is limited by their thickness, which should be about one quarter of the acoustic wavelength (1). Acoustic resonators e.g. Helmholtz resonators or $\lambda/4$ resonators, have a band limited absorption characteristic, which depends on the tuning frequency and inner damping (2). The tuning frequency and efficiency of acoustic resonators largely depends on the resonator back volume. Hence, due to the long acoustic wavelength at low frequencies, conventional silencer concepts require large installation space.

For applications where the installation space is limited active noise control (ANC) approaches can be an alternative. There are many different ANC concepts for various applications. In general, these approaches maybe subdivided in two main classes, feed forwards ANC and feedback ANC. Feed forward ANC requires an error and reference sensor (physical or virtual), a control transducer and a controller. In most practical applications, an adaptive control algorithm is implemented on a digital signal processor (DSP); an example for a feedforward ANC module for ventilation ducts is described in (3). Feedback ANC systems usually comprises a sensor-actuator pair, coupled via a feedback control loop. This feedback control loop may be implemented on a DSP or as an analog electronic circuit. In theory, feedback loops with perfectly collocated and mutual dual sensor-actuator pairs are unconditionally stable. However, practical feedback loops are only conditionally stable up to a

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maximum stable feedback gain and may produce unwanted control spillover effects. Hence, the gain of a feedback ANC system needs to be carefully tuned. Nevertheless, implementing a feedback controller using an analog circuit has the benefit, that the hardware costs and system complexity is relatively low. One example of a successful implementation are active resonator silencer cassettes (ASCs), which have been developed at the Fraunhofer IBP for more than two decades (4).

The second section of this paper gives a brief overview on the characteristics, the performance and some practical applications of 'classical' ASC-units and arrays, which have dimensions in the range of decimeters. The third section of the paper describes more resent work on ASCs, which has been focused on the design of much leaner ASCs with dimensions in the range of centimeters. The fourth section of the paper presents the key results on practical applications of lean ASC-units and arrays in a compact active noise control system for a partly opened sliding window (5), and a compact active silencer system for a round ventilation duct (6). Finally, the results are summarized and possible future work on lean ASC-units is discussed.

2. CLASSICAL ASC

An ASC comprises a loudspeaker mounted in an air thigh casing, a microphone, which is mounted in close vicinity of the loudspeaker membrane and an analog electronic controller circuit with adjustable gain. The basic components of a 'classical' ASC are shown in Figure 1a. In essence, a passive ASC is a mass-spring-damper system. The loudspeaker membrane is the mass and the membrane suspension and the enclosed air volume in the casing form the spring. Viscoelasticity in the membrane suspension and other effects introduces some damping to the resonant system. Figure 1b shows that the absorption coefficient of the passive ASC (control off) has a relatively sharp peak at around 125 Hz, which is the resonance frequency of the spring-mass-damper system. Closing the feedback loop around the microphone-loudspeaker pair (control on), amplifies the natural membrane movement around the ASC resonance frequency. Figure 1b shows that for the absorption coefficient of the activated ASC, the peak around 125 Hz is much wider in frequency and has a much higher amplitude. As reference, Figure 1b also shows the absorption characteristics of a porous absorber, which is not efficient at low frequencies.

a) b)

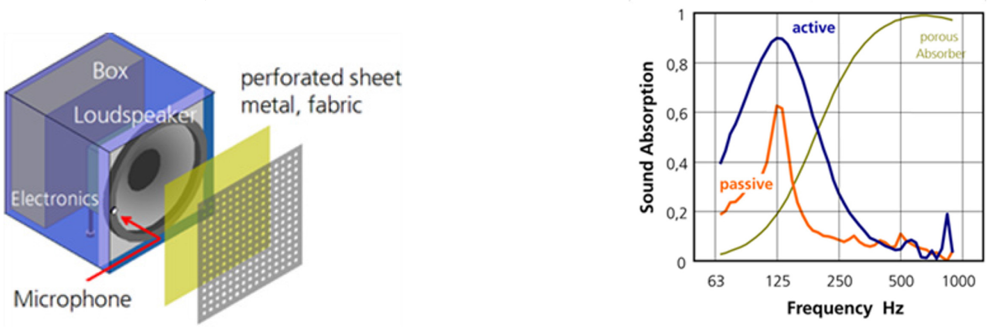

Figure 1 a) 3D drawing of an ASC; b) sound absorption coefficient (normal incidence angle) of a porous absorber and an ASC with open and closed control loop.

2.1 Classical ASC applications

In the past ASCs have been successfully applied as low frequency absorbers in various technical noise control applications (7, 8, 9). Figure 2 shows three concepts for ASC silencer systems. The first concept, shown in Figure 2a, comprises an ASC flush mounted in the wall of a duct, with porous absorption material mounted on the opposing duct wall. This concept is suitable for air ventilation ducts with relatively low flow speeds and normal climate conditions. The second concept, shown in Figure 2b, is similar to the first, but is specifically designed for the application in the exhausts of heating systems, where burners produce low-frequency noise. In such a system, the ASC is mounted in a branch of the duct in order to take it out of flow and to reduce the impact of high exhaust gas temperatures. It needs to be considered, that this influences the effective resonance frequency of the ASC. A foil is used to protect the electro-mechanical components from heat and condensate. The third concept, shown in Figure 2c, comprises an ASC mounted in a labyrinth wall opening. Such openings in walls of buildings and enclosures are often needed to provide pressure equalization, natural ventilation, suck in fresh air and expel exhaust gases.

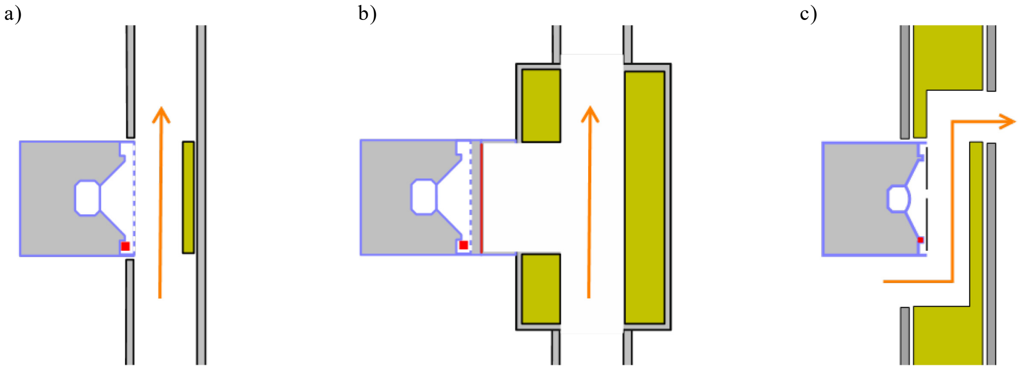

Figure 2 – Sketch of ASCs concepts for: a) an active duct silencer; b) an active silencer for heating systems; c) an active labyrinth wall opening.

Another typical application of ASC-Systems are splitter silencers for larger ventilation systems. As illustrated in Figure 3a, for this application usually arrays of ASCs are employed in combination with passive absorber splitters. As shown in Figure 3b, at low frequencies the insertion loss (IL) of the splitter silencer with ASCs is higher than for an equivalent splitter silencer employing only porous absorbers. In order to get a good broadband performance it is important to combine ASC-systems with appropriate porous absorbers. Towards high frequencies, the performance of splitter silencers is limited by the width of the gap between the splitters. The results in Figure 3b also illustrate an interesting effect; the attenuation maximum of the ASCs varies with the microphone position upstream or in the center axis of the ASC-loudspeakers. This has to do with the slight change in the delay between the acoustic signal picked up by the microphone and the loudspeaker reaction to it. This changes the open loop transfer function of the closed feedback control loop.

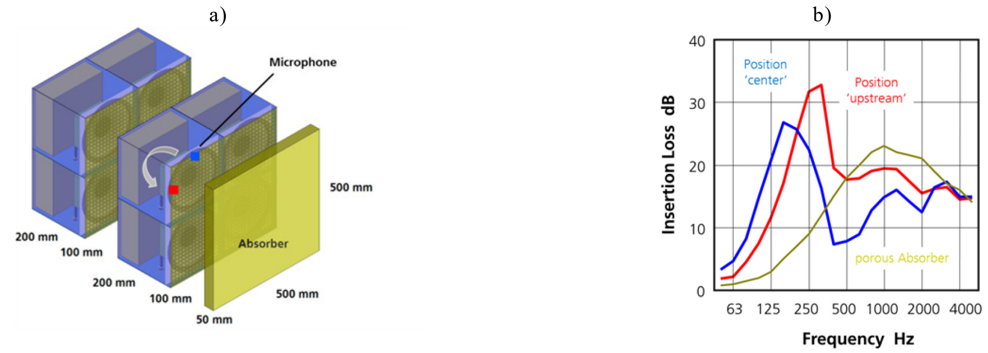

Figure 3 – a) 3D Sketch of ASC array splitters in a ventilation duct; b) The IL according to ISO 7235 (position of the ASC detection microphone is varied).

Figure 4 shows pictures of commercial applications of the active silencers concepts discussed above. All these practical systems provide significantly higher noise attenuation at low frequencies than porous absorbers of the same size. The main drawback is the relatively high costs of such silencer systems. Therefore, they have only be successful in applications where restrictions in installations space outweighed the increased costs.

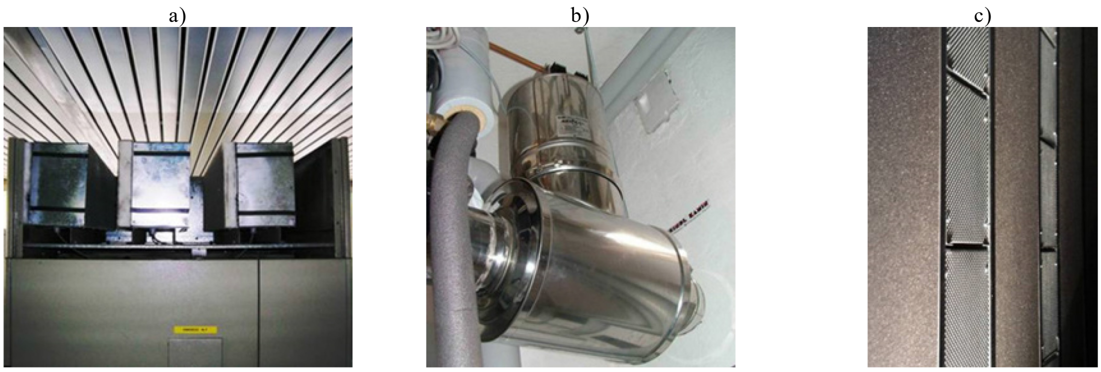

Figure 4 – Pictures of practical active silencer applications; a) ASCs top of a HVAC server unit; b) a compact active silencer at the exhaust side of a heating system; c) splitter silencer in a wind tunnel.

In all ASC applications, it is important to fine-tune the feedback gain of the ASCs in order to achieve good low frequency performance and to limit high frequency spillover effects. In appropriately designed and tuned silencer systems passive porous absorbers counter balance active control spillover effects of the ASCs.

3. LEAN ASC DESIGN

Classical ASCs have dimensions in the range of decimeters, i.e. 250x250x200 mm^3. This limits the range of applications to which they can be applied. For example the concept of an ASC in an labyrinth wall opening shown in Figure 2c would only be feasible for relatively thick wall constructions but not for thin walled lightweight enclosures. In addition, the production costs of classical ASC has proven to be too high for a wider commercialization. Hence, in order to widen the range of possible applications and reduce manufacturing costs, resent work on ASCs has been focused on the design of much leaner ASCs with dimensions in the range of centimeters, i.e. 50x50x50 mm^3. As indicated in Figure 5, the initial idea was to replace a ‘classical’ ASC by an 5x5 array of lean ASCs, which has the same effective area but only requires a quarter of the installation height. Scaling the dimensions of the ASC down by almost an order of magnitude comes with a number of design challenges. This section addresses the design challenges and discusses the characteristics of the lean ASC-units and ASC-line-arrays. The concept of a 5x5 ASC array has not yet been implemented.

a) b)

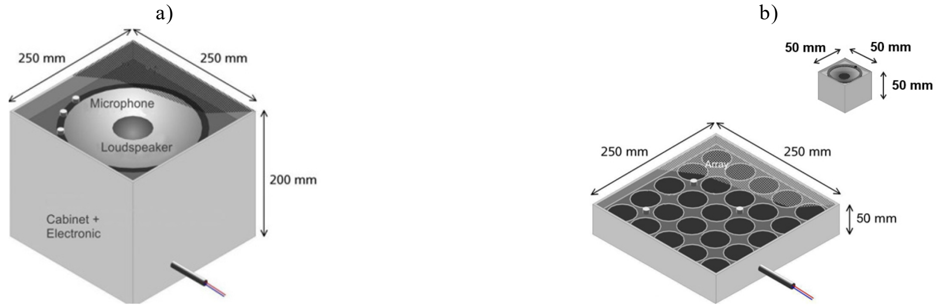

Figure 5 – a) Schematics of a ‘classical’ ASC and b) Schematics of a lean ASC design and a concept for a 5x5 array of lean ASCs with equivalent effective area as a ‘classical’ ASC.

3.1 Scaling and design of ASC arrays

As discussed in Section 2, a passive ASC is a mass-spring-damper system. Hence reducing the size of the loudspeaker and reducing the air volume enclosed by the casing, increases the resonance frequency. Furthermore, small loudspeakers have a lower stroke limit, which limits the maximum sound power output at low frequencies. This is contrary to the idea of using ASCs for the reduction of low frequency noise. In order to investigate concepts and components for lean ASCs a test set-up has been designed, which implements the ASC concept shown in Figure 2a. The set-up comprises a duct with a rectangular cross section of 50x50 mm^2 with a primary noise source at one end and an anechoic termination at the other. Figure 6a shows with Type A and Type C two examples of lean ASC designs that were investigated. Figure 6b shows the ILs for different types of ASC designs. Compared to the ‘classical’ ASCs, shown in Figure 1, the resonance frequency of the lean ASCs is about three to four times higher. Nevertheless, for some designs an IL of over 10dB is achieved in the frequency range between 125 Hz and 500 Hz. All lean ASC designs investigated produce control spillover effects in the frequency range between 800 Hz to 1000 Hz. This may be improved by optimizing the characteristics of the feedback loop control circuit.

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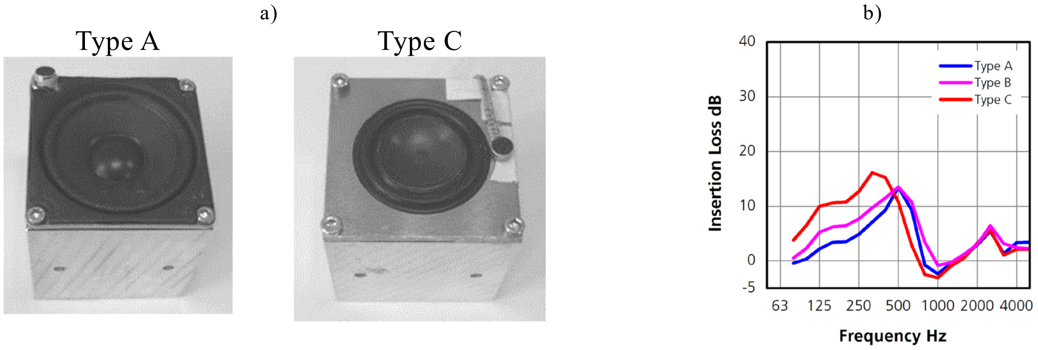

Figure 6 – a) Pictures of two lean ASC designs; b) results of the IL for three types of lean ASC designs.

Based on the results for single ASCs, the ASC design type ‘C’ was selected for studies on ASC-line arrays comprising a total of four individual ASCs in a decentralized Multi Input Multi Output (MIMO) feedback control scheme. Figure 7a shows a picture of the ASC line array. The results for the ILs with one, two, three or all four ASCs switched on simultaneous are presented in Figure 7b. The interaction between the individual ASCs reduces the stability of the MIMO system. Hence, the feedback gains were set such that the MIMO system, with all four ASCs switched on, remained stable. Therefore, the IL results for one active ASC are about 5 dB lower than those for a single type ‘C’ ASC shown in Figure 6b. Nevertheless, using all four ASCs simultaneously yields an IL of more than 20 dB in the frequency range between 125 Hz and 315 Hz. However, the more ASCs are used simultaneously the higher are the spillover effects in the frequency range around 800 Hz. This indicates that MIMO ASC systems need to be handled with care and that further investigations on the stability of the MIMO feedback loop are required for additional improvement of the performance.

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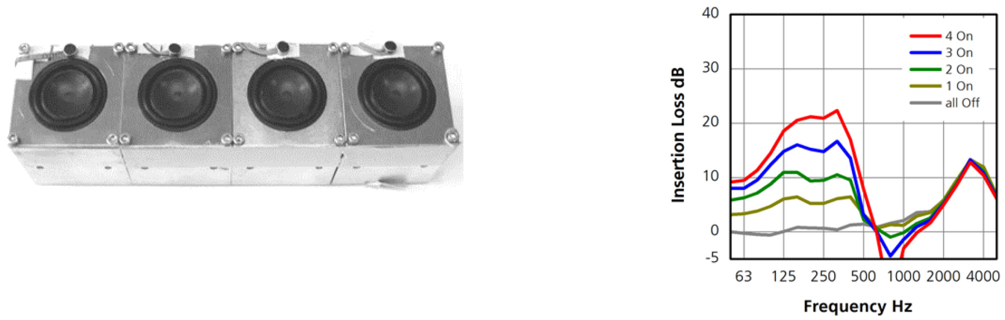

Figure 7 – a) Picture of a lean ASC line array; b) results of the IL for one, two, three or four active ASCs.

3.1.1 Application of activated carbon powder in the back volume

In order to arrive at an even smaller installation height of the ASCs without shifting the ASC resonance frequency further up, the stiffness of the back volume in the casing needs to be reduced. In ‘classical’ ASCs porous fibre material in the back volume is used to shift the resonance frequency, and the effective frequency range, down by a couple of Hz. One possible approach to drastically reduce the stiffness of the back volume is to evacuate the air. However, the low static atmospheric pressure in the back volume would require an entirely different transducer design, since conventional loudspeakers are not designed to operate at high static pressure differences (10).

Another efficient, more practical approach is the application of activated carbon in the back volume. Activated carbon is available in different forms, e.g. as granulates and powders. Investigations and studies on the acoustic absorption characteristics of activated carbon have shown that fine loose activated carbon powder is the best filling to reduce the stiffness of the back volume of the lean ASCs (11). Figure 8a shows a prototypical loudspeaker casing with activated carbon powder filling. The loudspeaker is mounted with the outside of the membrane facing into the loudspeaker casing. This is because otherwise the fine activated carbon powder would enter into the gap between the coil and magnet of the voice coil motor. Figure 8b shows the spectra of the sound power levels generated by a loudspeaker mounted in a reference casing and a casing, which only has a quarter of the reference volume, with and without activated carbon powder filling.

a) b) c)

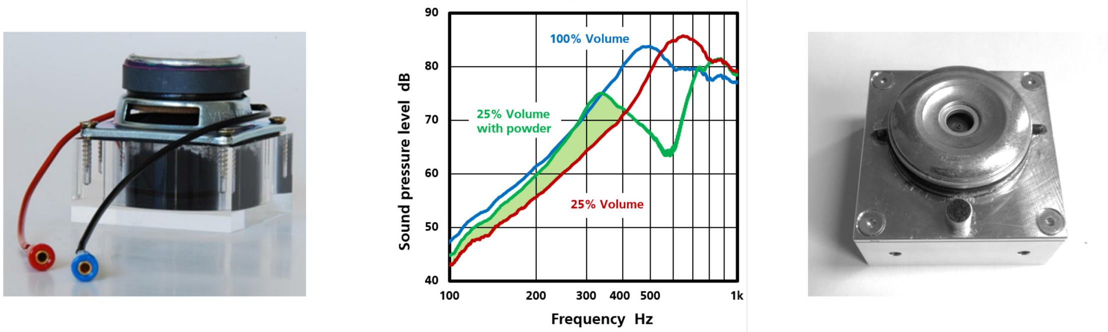

Figure 8 – a) prototypical loudspeaker casing with activated carbon powder filling; b) spectra of the sound power levels generated; c) picture of the resulting lean ASC design.

The results for the back volumes with carbon powder filling show that the resonance frequency of the loudspeaker system shifts towards lower frequencies by about one octave. Also, in the frequency range between about 250 Hz and 400 Hz the loudspeaker systems with small filled back volume and large empty back volume generate sound pressure levels of about the same magnitude. Using an activated carbon powder filling allows reducing the height of the lean ASC back volume to about 20 mm. Applying a loudspeaker with slim driver design allows to design a lean ASC unit with a total installation height of about 25 mm. Figure 8c shows the resulting lean ASC design.

4. LEAN ASC APPLICIONS

Scaling the dimensions of the ASC-units down by an order of magnitude widens the range of possible applications. This section presents the key results of two studies in which lean ASC-units are used to build up compact active silencer systems.

4.1 Sliding window with active gap

Open windows are probably the easiest and most common way to ventilate rooms. However, open windows, even if only partly opened, do not provide efficient sound insulation. Hence, especially in noisy urban outdoor environments opening a window can cause unwanted acoustic transmissions to the inside. A concept to tackle this problem are windows with acoustically muffled ventilation gaps. Based on the ASC application concept shown in Figure 2c, lean ASC units where used to design an active noise control system for a partly opened sliding window (5). Figure 9a shows the 3D drawing of a sliding window. On the right hand side, the opening frame is extended with an L-shaped profile, which overlaps with the wall and ranges over the entire height of the window. Figure 9b illustrates, that this extension forms a labyrinth gap when the window slides partly open. At the end of the extension profile, a line array, consisting of 20 lean ASCs is installed to actively reduce low frequency noise transmission through the gap to the inside. Figure 9c shows one segment of the ASC line array, which itself consist of four individual ASC units.

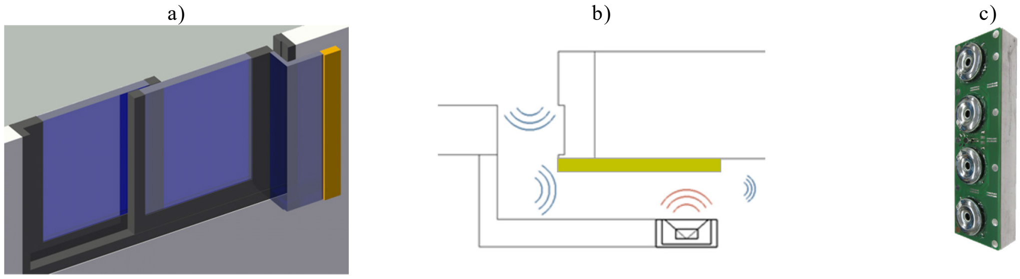

Figure 9 – a) 3D drawing of a sliding window; b) illustration of the labyrinth gap with ASCs; c) picture of a segment of the ASC line array.

After preliminary studies, a prototypical life size window was constructed and installed in a sound transmission chamber, as shown Figure 10a. The results for the sound transmission loss (STL) measurements for the closed window, the open window without labyrinth profile, the open window with passive labyrinth profile and the open window with labyrinth profile and activated ASCs are presented in Figure 10b. The STL of the open window without acoustic treatment has a significantly lower STL than the closed window. The STL of the open window with passive labyrinth is similar to the STL of the window without acoustic treatment, except for frequencies above 1800 Hz where the passive treatment in the labyrinth gap becomes effective.

Figure 10 – a) prototypical window installation in the test chamber; b) results of the STL measurements.

In the frequency range up to 400 Hz the STL of the open window with ANC is almost as high as the STL of the closed window. The weighted STL of the open window with ANC is about 4 dB higher than that of the open window without acoustic treatment. However, the relatively poor STL in the frequency range between 400 Hz and 2500 Hz limits the value of the weighted STL. However, overall the results of the experimental studies on the sliding windows with active gap are promising. Shortcomings that result in the poor STL in the frequency range between 400 Hz and 2500 Hz may be overcome by developing passive acoustic treatments that compensate the active control spillover effects and cover the high frequency range more efficiently.

4.2 Active silencer for a round ventilation duct

Due to increasing requirements on energy efficiency and air tightness of buildings, forced ventilation systems are increasingly popular even for domestic dwellings. Hence, there is an increasing demand to reduce noise from Heating Ventilation and Air Conditioning (HVAC) systems. As discussed in the introduction, silencers for the control of low frequency noise require a relatively large installation space. By extending the ASC application concept, shown in Figure 2a, lean ASC units where used to design a compact active silencer system for a ventilation duct (6). The test set-up comprises a duct of circular cross section with a diameter of 130 mm, with a primary noise source at one end and an anechoic termination at the other. Figure 11a shows the basic ASC set-up including a 20 mm thick porous absorption layer. Figure 11b shows a view into the duct.

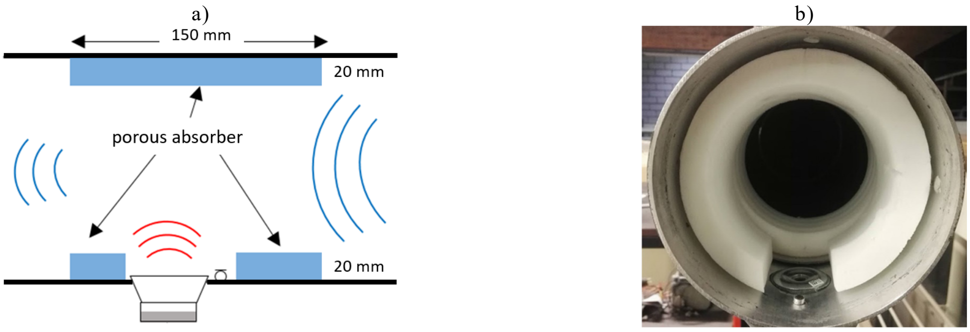

Figure 11 – a) Sketch of the ASC set-up; b) picture of the view into the duct.

In the study various configurations of the active silencer components have been investigated, most notably the application of multiple control loudspeakers. Figure 12a shows the four principal control configurations considered a) a single ASC b) two ASCs mounted opposite of each other at an angel of 180°, c) three ASCs mounted at angles of 120° and d) four ASCs mounted opposite of each other at angles of 90°. For simplicity, only the signal of one single microphone sensor was fed back in phase to all ASC-loudspeakers simultaneously. This reduces all configurations to a Single Input Single Output (SISO) feedback control system. The benefit of using two or more loudspeaker driven in phase is that the first cross-section mode of the duct at around 1547 Hz is not excited efficiently. Using three or more loudspeaker driven in phase results in an acoustic ring source (12), which does not efficiently excite higher cross-section modes of the duct. Figure 12b shows the results of the IL for all four ASC configurations. With increasing numbers of ASC-loudspeakers, the IL in the low frequency range up to about 600 Hz is increasing. For the configuration with three and four loudspeakers an IL of over 14 dB is achieved around 200 Hz. However, with increasing number of ASC-loudspeakers the active control spillover effects around 1000 Hz are also increasing. For the configurations with one and two ASC-loudspeakers the passive porous absorption layer compensates the active control spillover. For the configuration with three ASC-loudspeakers, the control spillover effects are barely compensated. For the configuration with four ASC-loudspeakers the control spillover exceed the IL provided by the passive absorption layer, resulting in a negative overall IL in the frequency range between 800 Hz and 1000 Hz. However, the results of the experimental studies on active silencers for a round ventilation duct with a SISO feedback control scheme are promising and encourage further investigations. Within this study, the stability of the feedback control loops was systematically investigated by measuring and analysing the open loop transfer functions of the feedback loops. This analysis provided interesting insights and hints for possible improvements. Further studies may investigate a SISO control system configuration that utilises the summed signal of all four ASC-microphones and a completely decentralised MIMO control scheme with four individual ASCs.

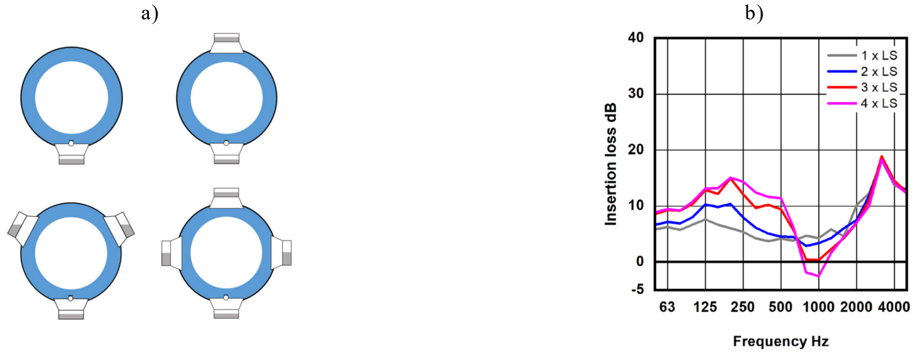

Figure 12 – a) sketch of four control ASC configurations; b) results of the IL for ASC configurations employing one, two, three or four ASC-loudspeakers.

5. CONCLUSIONS

This paper has given a brief overview on the characteristics, the performance and some practical applications of 'classical' ASCs, which have been developed at the Fraunhofer IBP over the last two decades. More resent work on lean ASCs has been presented, especially issues with the downscaling of the ASCs has been addressed and discussed in more detail. Due to their compactness, lean ASCs have a wider application range than 'classical' ASCs. In this paper, the key results of studies on practical applications where lean ASCs are used in a compact active noise control system for a partly opened sliding window and a compact active silencer system for a ventilation duct have been presented. The results are very promising. However, all studies on lean ASCs have shown that their performance is limited by active control spillover effect in the frequency range between 800 Hz and 1000 Hz, especially for configurations where multiple ASCs are used simultaneously. In order to improve the performance, further studies are needed to investigate the stability of SISO and MIMO ASC-systems. The aim of the Fraunhofer IBP is to develop innovative, commercially viable noise control concepts and products based on lean ASCs.

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