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Principy a perspektivy aktivního snižování hluku

Principles and Perspectives of Active Noise Control

Summary

Human health and the quality of life are greatly affected by various environmental disruptions. Significant agents in this area are noise and vibration; hence, their reduction is a concern for a great number of research laboratories, as well as project and consulting companies.

The traditional approach to acoustic noise control uses passive techniques such as enclosures, barriers, and silencers to attenuate the undesired noise. Active noise control (ANC) consists in adding a secondary wave created by artificial sources to the incident wave produced by the noise source, so that the superposition of these waves cancels the sound. Lecture deals with basic principle and some practical applications of ANC system. The first serie of experiments was performed on a duct of round and rectangular cross-section located at the Department of Physics at CTU in Prague. In the ducts of relatively small cross-section, in which only waves below the cut-off frequency can be assumed, a single channel ANC system can be used. For a larger duct, when the condition for development of higher order modes is fulfilled, the multi-channelANC system has to be used. In the duct of rectangular cross-section system up to four channel was used, which in principle should enable suppression of zeroth mode and the first three higher order modes. The second serie of experiments was used for local principle of ANC – formating of zones of quiet around a passenger’s head. Such a system can be mounted in the headrest of the seat. The system was tested with two configurations of secondary sources.

A feed-forward ANC system with microphones as reference and error sensors requires identification of the transfer function from the digital controller outputs to corresponding inputs to ensure convergence of the algorithm used; *x*-LMS algorithm was assumed. Sufficiently large FIR filters spend significant portion of controller memory and computational time. This can be solved by using IIR filters, which can be obtained by solution of Prony equations to minimize a error function.

At present, we can see more and more areas for applications of this methods. The ANC systems can now be used in many practical areas of acoustics and vibration. Even if we are speaking about commercial applications of ANC, there are still many varied problems to solve. Attention can be drawn to the new, more effective algorithms, new kinds of transducers (particularly actuators), searching of new areas especially in the field of active control of three-dimensional sound fields and vibrations.

Souhrn

Kvalita našeho života a naše zdraví jsou ovlivňovány různými faktory životního prostředí. Důležitými fyzikálními faktory jsou i hluk a vibrace, proto je jejich snižování zájmem řady výzkumných laboratoří, stejně jako projektových nebo konzultačních organizací.

Obvyklý přístup při snižování hluku spočívá v použití pasivních technik jako jsou kryty, bariéry a tlumiče hluku. Princip aktivního snižování hluku (ANC) je založen na vytvoření sekundární vlny generované dodatečným zdrojem. Z principu superpozice vyplývá, že za určitých okolností dojde ke snížení velikosti zvukového pole. V přednášce jsou popsány praktické realizace využívající metod aktivního snižování hluku. První část experimentů byla provedena na potrubí kruhového průřezu umístěného v prostorách katedry fyziky ČVUT–FEL. Potrubí mělo vnitřní průměr 10 cm, a proto jsme předpokládali že se jím bude šířit pouze rovinná vlna. Proto také byl použit jednokanálový systém ANC. Pro potrubí větších průřezů, kdy není splněna podmínka šíření pouze rovinné vlny, je nutné použít vícekanálový systém ANC. Pro potrubí obdélníkového průřezu byl použit až čtyřkanálový systém, který je schopen potlačovat rovinnou vlnu a první tři příčné módy. Druhá část experimentů se týkala využití lokálního principu ANC – generování zón ticha v okolí posluchačovy hlavy. Takovýto systém může být umístěn například do podhlavníku sedadla. Systém byl testován se dvěmi konfiguracemi sekundárních zdrojů.

Aplikace využívaly algoritmus adaptivní filtraci *x*-LMS. Ten při použití v ANC systému se strategií *feed-forward* – při využití mikrofonů pro získání referenčního a chybových signálů – vyžaduje implementaci modelů chybových a zpětnovazebních cest. Pro tyto modely je možné použít FIR filtry, avšak ty při větší délce zabírají hodně paměti a výpočetního výkonu digitálního signálového procesoru. Jako výhodné se jeví použití IIR filtrů, jejichž koeficienty mohou být získány řešením Pronyho rovnic.

V současnosti můžeme vidět stále více oblastí aplikace aktivních metod. ANC systémy mohou být nyní využívány v mnoha praktických oblastech akustiky a vibrací. Nicméně i v oblasti komerčních aplikací je stále dost prostoru pro výzkum a vývoj. Pozornost je třeba zaměřit především na nové, efektivnější algoritmy, nové účinnější algoritmy, nové typy převodníků (zejména aktuátorů) a hledání nových oblastí aplikací. Ty lze očekávat především pro aktivní řízení zvuku v obecném trojrozměrném prostoru a pro snižování vibrací.

Klíčová slova: akustika, vlnová rovnice, aktivní snižování hluku, akustické aplikace, zóny ticha, měření, historický přehled

Keywords: acoustics, wave equation, active noise control, acoustic applications, zones of quiet, measurements, historical overview

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Contents

1 Introduction

Human health and the quality of life are greatly affected by various environmental disruptions. Significant agents in this area are noise and vibration; hence, their reduction is a concern for a great number of research laboratories, as well as project and consulting companies. The clasical approach to noise control is based on minimization of the generation of sound or vibrational energy by improving the mechanical quality of the source of noise. The second step usually consists in breaking transfer paths or at least minimizing sound energy transfer from the source to the human being. One of the relatively new approaches to noise control is active noise control (hereinafter ANC), which appears very promising thanks to its effectiveness primarily at low frequencies. This technique is primarily focused on the global or local reduction of sound pressure or acoustic energy density in the air in the vicinity of human subjects. Methods based on the classical principle will be hereinafter called passive methods and the ANC methods will be called active methods.

Principles of active noise control are based on knowledge in the field of mechanics particularly acoustics. Nevertheless, for practical realisations at present, we also need a strong knowledge of signal processing techniques, as the greater part of ANC systems are equipped with DSP controllers.

2 Principle of active noise control

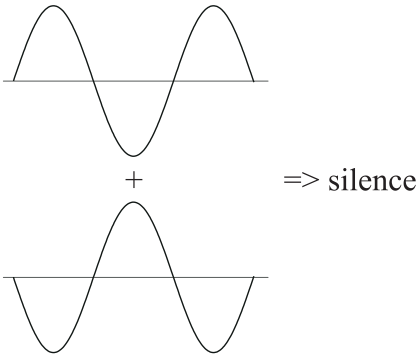

Figure 1: Composition of two sinus waves

In principle, active control of noise and vibrations is based on interference of sound waves propagating through air or structure. In air, the primary wave generated by the source of noise is eliminated by a secondary wave produced by the ANC system, which differs from primary wave only in having the opposite phase. The basic principle is demonstrated simply in Figure 1. In spite of the fact that there is only one physical principle of active control, in literature we can find that the active methods are divided into three categories: wave interference, acoustical coupling, and modal control [1].

The former category can be assumed in local control when the waveform generated by the secondary source is controlled in such a way as to interfere destructively with the primary source in a given region of space, resulting in local reduction of sound pressure in that region. A similar approach can be assumed in the one-dimensional case (e.g. in a duct) where the secondary wave is propagated along with the primary wave. The efficiency of such a method is strongly dependent on phase and amplitude matching of both primary and secondary waves. The theoretical reduction of sound pressure level is shown in figure 2 [2], which illustrates how closely the secondary pressure fluctuations must be matched to the primary fluctuation in its amplitude and phase in order to produce appreciable reductions in the level of the total sound pressure. Phase matching is usually more complicated and in order to produce a 20 dB reduction in level the phase must differ by no more than $\vartheta \leq 4.7°$. For reduction of 30 dB we need $\vartheta \leq 2.8°$.

The special case of the former category can be described as application of Huygens' principle. The basic idea, developed by Jessel in the sixties [3], is shown in Figure 3.

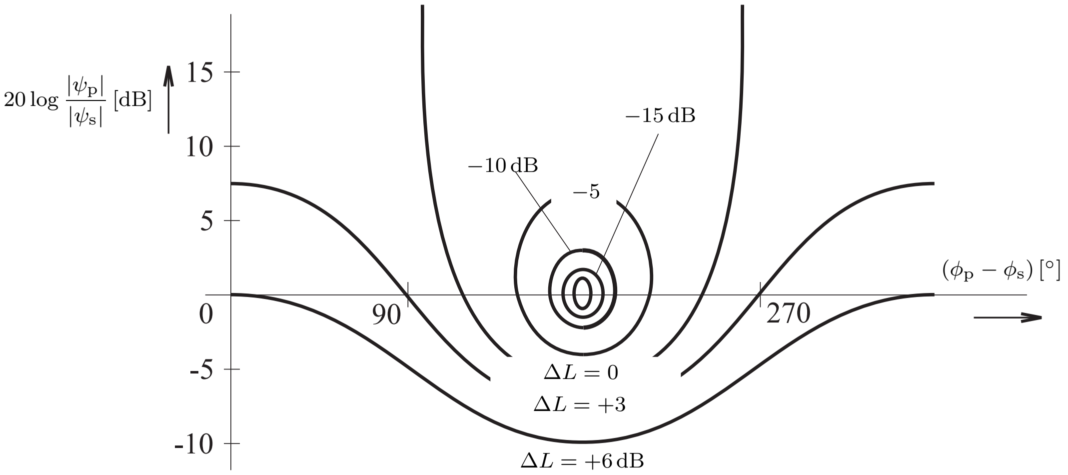

Figure 2: Maximum reduction of sound pressure level as a function of phase and amplitude mismatch

Let us assume primary point source producing spherical waves as shown in Figure 3a). As every point of the wavefront can be assumed to be a point source, we can generate the same sound field by an infinite number of sources distributed over such a wavefront (see Figure 3b)). But if we adjust this elementary sources to be out of phase, we obtain standing waves inside of the sphere but no sound field outside (see Figure 3c)).

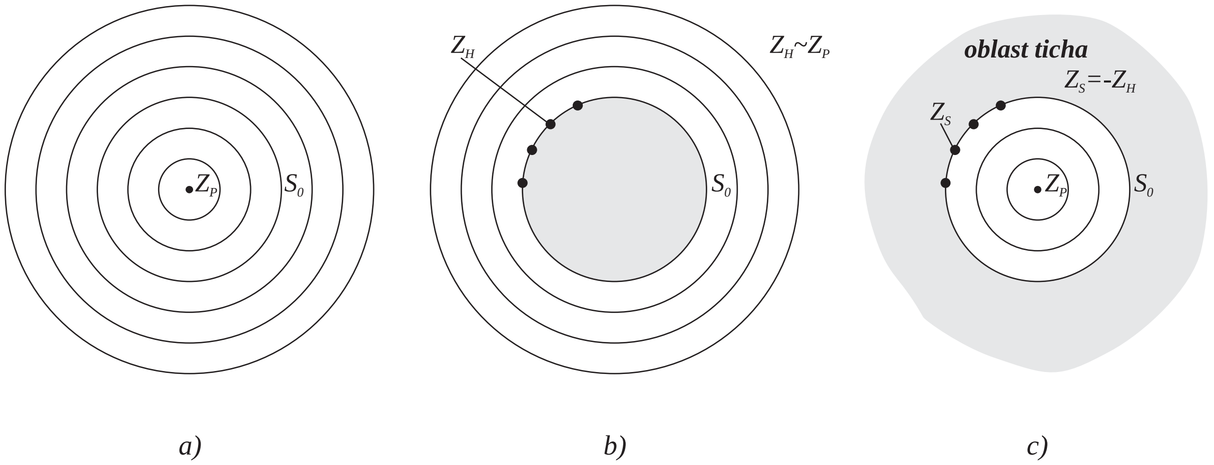

Figure 3: Application of Huygens principle

In the case when we are able to localize the primary source of sound, it is possible to control its radiation through the secondary source (or sources) located close to them. This approach is called acoustical coupling. When the distance between a simple primary source and the secondary source is small in relation to the wavelength of the sound being canceled, then by driving the secondary source out-of-phase from the primary source, the radiation efficiency of both sources together is smaller than the radiation efficiency of the primary source. It results in global reduction of the sound pressure of sound energy density.

The third possible method is called modal control, and can be used in enclosed spaces at low frequencies when the modal behavior of the system being controlled is well defined. In this case, the magnitudes of the individual modes in the space are reduced by appropriately located and controlled secondary sources. Theoretical analysis shows that reasonable results can be achieved only at such low frequencies when low modal density can be assumed. Depending on enclosure size and the number of modes to be canceled, a large number of sensors and secondary sources is needed.

3 Historical overview

Even though notes on the possibility of cancelling sound by sound can be found in the works of Helmholtz or Lord Reyleigh in the nineteenth century [4], the basic idea of active noise control (ANC) is usually linked to the name Paul Lueg, the German invertor who applied for US patent in 1933. He proposed two possible applications of active noise control, the first for cancellation of sound in a duct and the second for active cancellation in three-dimensional space. The first mentioned application of ANC in a duct was in particular very close to today's approach to the problem (see Figure 4).

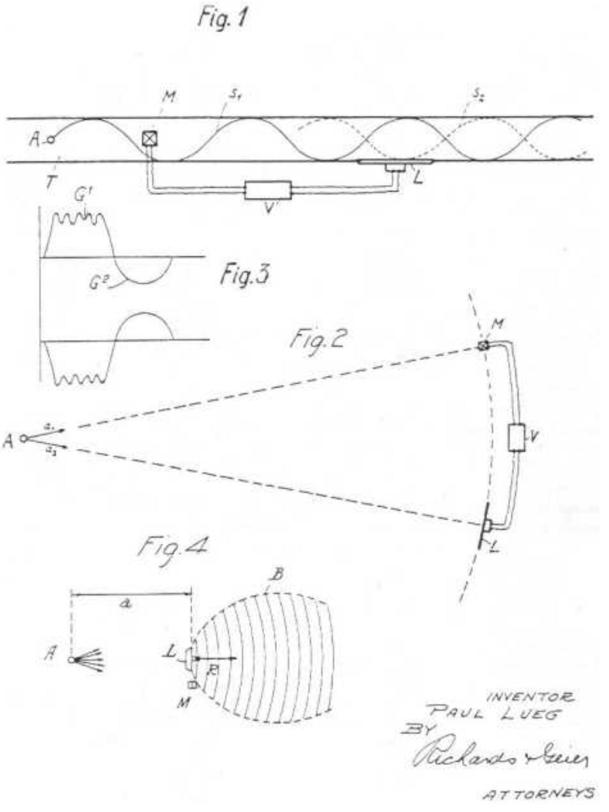

Figure 4: Facsimile of Lueg's patent

In 1953, Olson and May reported on experiments with active control using a so-called active absorber [5]. This active absorber was an analog feedback system based on a loudspeaker and microphone located close together. Its application was assumed in various areas of daily life to create so-called zones of silence around the human head. Even though their "electronic sound absorber" was tested in laboratory conditions, most of the suggested applications was realized only later, using more sophisticated, usually digitally controlled, systems.

In 1965 Conover from General Electric tried to decrease the sound radiated by a relatively large transformer (15 MVA). Conover's approach was to place loudspeakers near the transformer's surface and cancel the pressure radiation in the near field. Conover used a 60 Hz transformer producing 120, 240, and 360 Hz harmonics. For the generation of control signals, he used an electric signnal and therefore acoustic feedback was eliminated. After adjusting each frequency component in amplitude and phase, the signals were recombined, amplified, and fed to a loudspeaker placed at the centre of one of the flat faces of the transformer, obtaining reduction of up to 12 dB in that direction [6]. His experiments were in fact an application of Huygens' principle.

In the 1980s, rapid development of active method in acoustics occured mainly thanks to huge development of new technologies.

4 Active noise control in a duct

In this paragraph we will discuss the most simple ANC system from the acoustical point of view. Let us assume that we have a one-dimensional sound field only. This kind of sound field can be found in a narrow waveguide or a duct of constant cross-section under condition of linear acoustics [8]. Only plane wave propagation can be assumed for following wavelenghts λ:

$$\lambda > 1,7d, \text{resp.} \quad \lambda > 2h, \tag{1}$$

where d is the diameter of a circular duct and h is the larger dimension of rectangular duct respectively. The wave equation for the duct without flow then has the form:

$$\left(\frac{\partial^2}{\partial t^2} - c_0^2 \frac{\partial^2}{\partial x^2}\right)\psi = 0, \tag{2}$$

where c_0 is speed of sound. The general solution of this equation was found by d'Alambert, but we will assume harmonic motion, so the solution has the form:

$$\psi(x,t) = Ae^{\mathrm{i}(\omega t - kx)} + Be^{\mathrm{i}(\omega t + kx)}, \;\; k = \omega/c_0. \tag{3}$$

The first term describes a harmonic wave with magnitude A travelling in the positive x direction, and the second term describes a harmonic wave with magnitude B travelling in the negative direction.

If the fluid (air) moves in a waveguide in direction x with speed U constant through the whole crossection, the partial derivative with respect to time $\partial/\partial t$ must be replaced with the total derivative:

$$\mathrm{D}/\mathrm{D}t = \partial/\partial t + U\,\partial/\partial x. \tag{4}$$

The wave equation then has the form

$$\left(\frac{\mathrm{D}^2}{\mathrm{D}t^2} - c_0^2 \frac{\partial^2}{\partial x^2}\right)\psi = 0. \tag{5}$$

The solution of this equation can be obtained by separation of variables.

$$\psi(x,t) = Ae^{\mathrm{i}(\omega t - \omega x/(c_0+U))} + Be^{\mathrm{i}(\omega t + \omega x/(c_0-U))}, \tag{6}$$

where the meaning of magnitudes and directions of propagation is the same as in a wave equation without motion. Nevertheless, the speed of fluid motion is usually much smaller than the speed of sound and wave equation (2) with solution (3) can be a sufficiently good approximation.

For the description of the sound field in a narrow duct, we introduce a plane monopole source as a basic element. If we ignore the details of the oscillatory flow produced by the loudspeaker cone in its immediate vicinity, then the net effect on the sound field can be represented by a plane source which effectively generates the same plane wave field as the loudspeaker in the upstream and downstream directions. The plane source can be visualised as two massless pistons separated by an infinitesimal distance which are forced to oscillate apart b the introduction of a fluctuating volume flow (see Figure 5). Let us assume that we have a plane monopole source of source strength q_p at $x = 0$ located in an infinite duct. Then the complex pressure produced by the source can be written as

$$p_p(x) = \frac{\rho_0 c_0}{2S} q_p e^{-\mathrm{i}k|x|}. \tag{7}$$

If the source of source strength q_s is located at the position $x = L$, then the complex pressure produced by the source can be written as

$$p_s(x) = \frac{\rho_0 c_0}{2S} q_s e^{-\mathrm{i}k|x-L|}. \tag{8}$$

The total complex pressure produced by both sources acting indepently can be obtained by the superposition of both pressure fields:

$$p(x) = p_p(x) + p_s(x). \tag{9}$$

For practical reasons, let us consider the situation illustrated in Figure 5. The primary source is located at the end of the duct that can be described by reflection coefficient R. The complex pressure produced by the primary source is now:

$$p_p(x) = \frac{\rho_0 c_0}{2S} q_p e^{-\mathrm{i}kx}(1+R) \tag{10}$$

The similar situation will be for the secondary source.

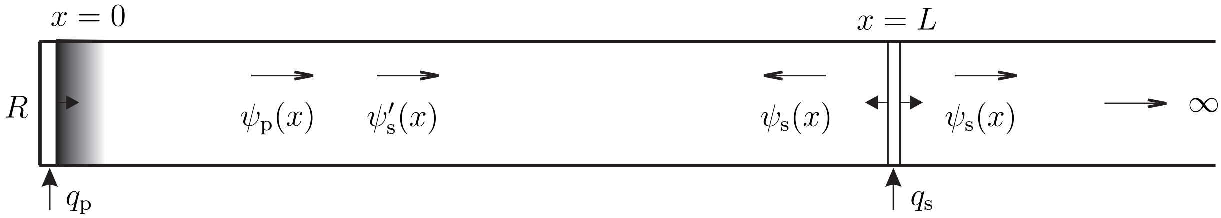

Figure 5: ANC in a duct

The objective of the ANC is to control secondary source so that the sound pressure field is zero in the chosen region. Let us require having a zero pressure field downstream from the secondary source:

$$p(x) = 0, \quad \text{for} \quad x > L. \tag{11}$$

The complex pressure in this region can be written as

$$p(x) = \frac{\rho_0 c_0}{2S} \left[q_p(1+R) + q_s \left(e^{\mathrm{i}kL} + Re^{-\mathrm{i}kL} \right) \right] e^{-\mathrm{i}kx}, \quad x > L \tag{12}$$

To provide perfect cancellation downstream from the secondary source, the secondary source strength must be:

$$q_s = -q_p \frac{1+R}{e^{\mathrm{i}kL} + Re^{-\mathrm{i}kL}} \tag{13}$$

Note that if $R = 1$, which corresponds to the case when the primary source reflects sound perfectly with no change of phase, then the equation (13) reduces to

$$q_s = -\frac{q_p}{\cos(kL)} \tag{14}$$

From this equation, it follows that there are some frequencies for which the secondary source strength necessary to cancel the field becomes infinite.

$$f = \frac{c_0(2n+1)}{4L}, \quad n = 0, 1, 2, \ldots \quad \Rightarrow \quad q_s \to \infty \tag{15}$$

In some special cases we are interested in the pressure field in the region between the sources. If the condition (13) is fulfiled, then this pressure can be described by the following formula:

$$p(x) = \frac{\rho_0 c_0}{2S}\left[q_p(1+R)e^{-\mathrm{i}kx} + q_s\left(e^{-\mathrm{i}k(L-x)} + Re^{-\mathrm{i}k(L+x)}\right)\right], \quad 0 < x < L \qquad (16)$$

We can find that for some specific distances between the sources and frequencies, there will be standing waves in this region.

Now we will discuss one practical example of ANC in a duct. In the ducts of a relatively small cross-section, in which only waves below the cut-off frequency can be assumed, a single-channel ANC system can be used. For a larger duct, when the condition for development of higher order modes is fulfilled, the multi-channel ANC system has to be used.

To control sound waves including the first cross-mode, two secondary sources (usually loudspeakers) should be implemented. The resulting sound field downstream in the duct is then monitored by two error sensors (usually microphones) as schematically represented in Figure 6. The reference signal is picked up by the reference microphone located at a certain distance from the secondary sources. The arrangement of the ANC system described above is predetermined for filtered-x LMS algorithm which, in comparison to the single channel system, contains a second channel and cross-relation between channels.

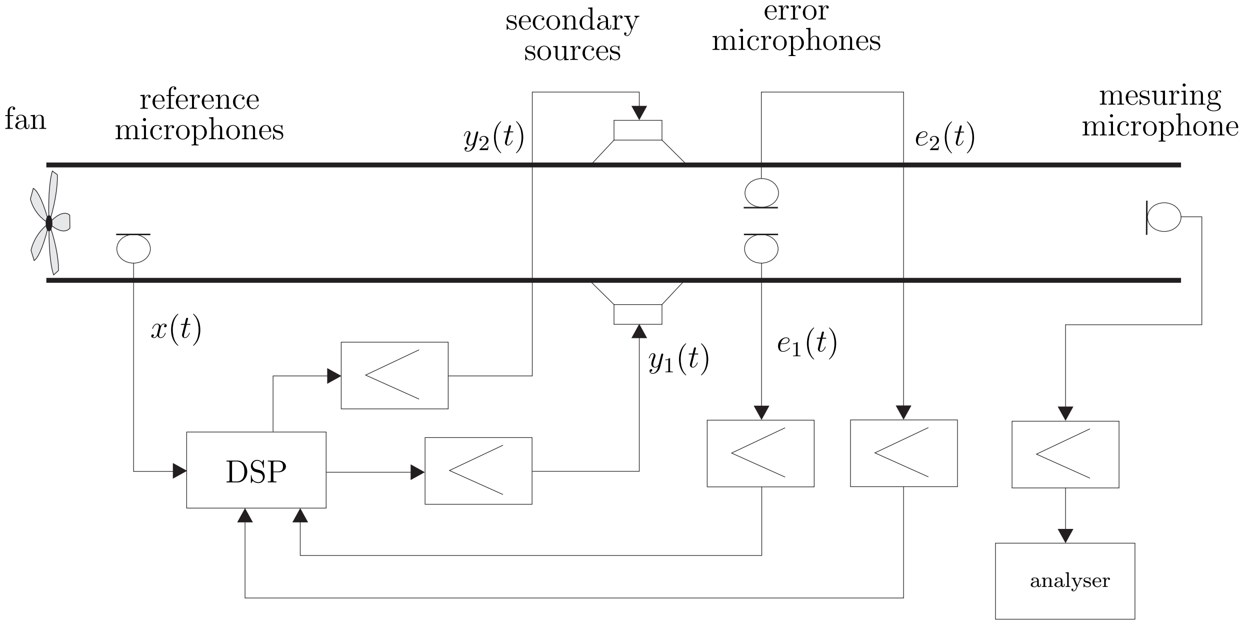

Figure 6: Two-channel ANC system in a duct

From the block diagram in Figure 7 (in $1\times2\times2$ version), it follows that for the correct function of the algorithm, sufficent precision is important in the modelling of error paths $\hat{C}_i(z)$, representing estimates of transmissions from the outputs of the control unit to its error inputs. As the reference signal is affected by acoustic feedback, models of the feedback paths $\hat{F}_k(z)$ are necesary too. This scheme of ANC system can be extended for an arbitrary number of secondary sources and error sensors.

Usually, for implementation of the models of error and feedback paths, FIR filters are used in the DSP representing the controller. Coefficients for FIR filters can be obtained from the initial portion of the measured impulse response. The disadvantage of these

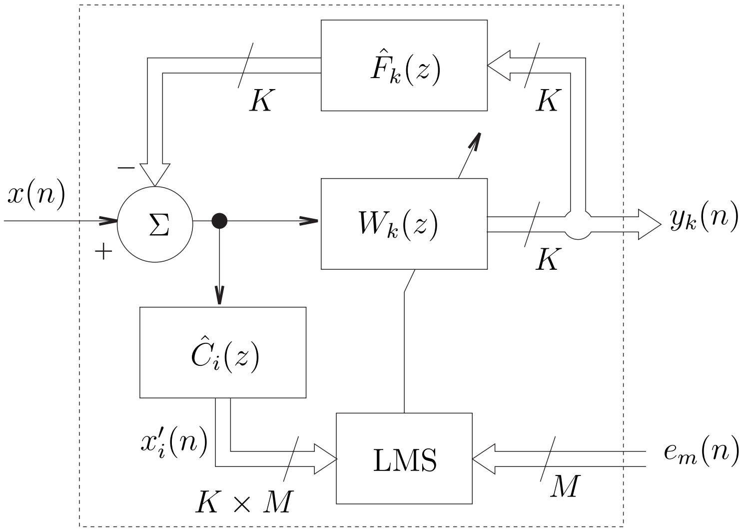

Figure 7: Block diagram of $1 \times K \times M$ ANC system.

models is that the impulse response is finite, and improvement of quality can only be achieved by increasing the number of coefficients which results in increased demands of calculation.

The second possiblility is to use IIR filters. The coefficients of these filters can be obtained by one of the usual identification methods of ARMA models. In the present case, the Prony method in combination with the Steiglitz-McBride adaptive algorithm was used.

Experiments were performed on a duct of rectangular cross-section of dimension of 200×300 mm. An axial flow fan with five blades and maximum volumetric flow rate up to 1.5 cubic meters per second was used. Flow speed was regulated by regulation of fan revolutions.

High pass filters of 100 Hz were implemented at all inputs of the controller [9]. For modelling of error paths, the IIR filters of 20th order were used. For feedback paths the order of 40 was chosen. Examples of attenuation of fan noise are shown in Figure 8.

5 Example of local control

From the physical point of view, active noise control in a free field is based on the solution of the inhomogeneous wave equation [2]. Sound pressure in a sound field due to source located in $\boldsymbol{y}$ is given by the following formula:

$$p(\boldsymbol{x}) = \int_V Q_{vol}(\boldsymbol{y}) G(\boldsymbol{x}|\boldsymbol{y}) \mathrm{d}V + \int_V [G(\boldsymbol{x}|\boldsymbol{y}) \nabla_y p(\boldsymbol{y}) - p(\boldsymbol{y}) \nabla_y G(\boldsymbol{x}|\boldsymbol{y})] \cdot \boldsymbol{n} \mathrm{d}S \tag{17}$$

In the particular case of a point monopole source at $\boldsymbol{y}_1$ where $q_{vol}(\boldsymbol{y}) = q\delta(\boldsymbol{y} - \boldsymbol{y}_1)$ performing the volume integral yields

$$p(\boldsymbol{x}) = \frac{\mathrm{i}\omega\rho_0 q \exp(-\mathrm{i}k|\boldsymbol{x} - \boldsymbol{y}|)}{4\pi|\boldsymbol{x} - \boldsymbol{y}|} \tag{18}$$

which is the familiar expression for the complex pressure produced by a point monopole source.

Zone of quiet is defined as a region in which the sound pressure level is suppresed by more than 10 dB. Theoretical calculation of zones of quiet can be found in Figure 9, using

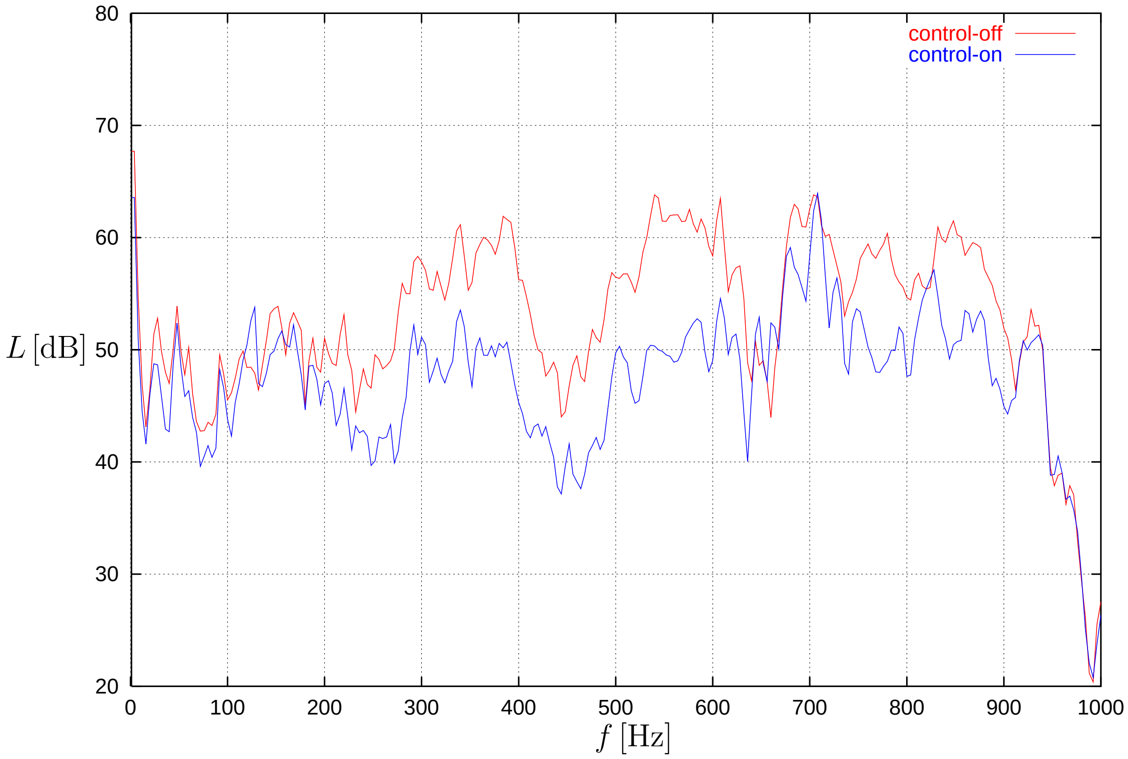

Figure 8: Broad-band noise reduction in a duct

the principle of superposition for two monopole sources. The secondary source is adjusted to have double source strength then the primary source and phase shift $\phi = 1\,\mathrm{rad}$.

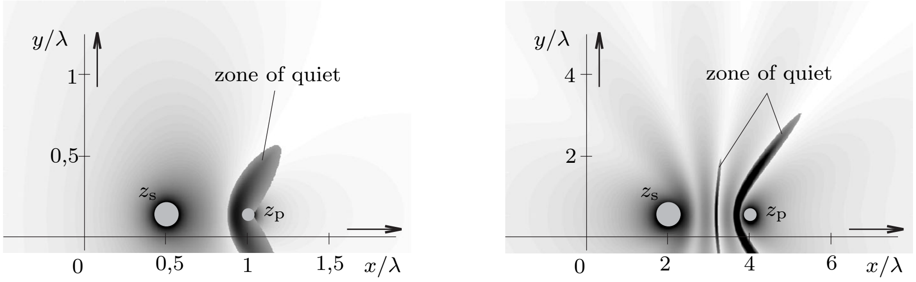

Figure 9: Zones of quiet for point sources in distances of 0,5λ and 2λ

We will now take care of one practical example of local ANC. From point of view of noise control, global control is the most desirable result of active noise control designers. Nevertheless, in many situations it is unrealistic or physically impossible to achieve global control. In such situations, local active control can be an acceptable and advantageous solution. One of the practical applications of local active noise control is in the formation of zones of quiet around a passenger's head [10]. Such a system is usually mounted in the headrest of the seat. Two such configurations of secondary sources located in headrest have been tested.

The arrangement and performance of a two-channel local active noise control system acting in well-defined sound field conditions (free field) is described in this section. As the diameter of the zone of quiet within which the sound pressure level is decreased by about 10 dB or more, is about 0.1λ, the system is useful for low frequencies of up to

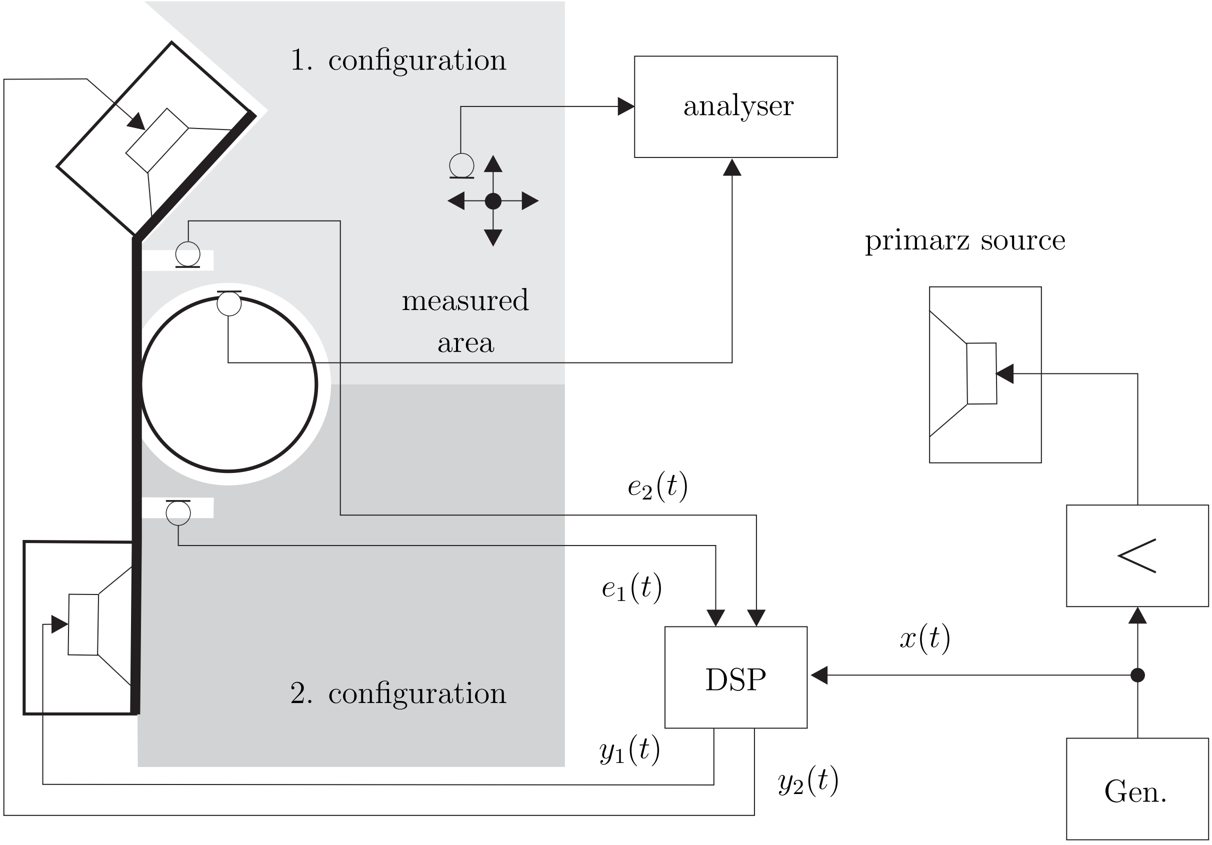

Figure 10: Experimental setup for local ANC

approximately 500 Hz. The development of the shape of zones of quiet with respect to the frequency and spatial arrangement of secondary sources was studied.

A common seat is equipped with a robust headrest, which contains two secondary loudspeakers with a diameter of 14 cm in the back side and holes for two error microphones close to the position of human ears. In the first configuration, the plane of the secondary sources makes a 45° angle to the back of the seat. In the second configuration, the secondary sources were in one plane with the back of the seat. Both configurations are depicted in Figure 10. The ear channels were at the same height as the centers of the secondary loudspeakers and error microphones. The distance between error microphone and ear channel is approximately 7 cm.

For the purpose of field mapping the seat with active headrest was located in the middle of the measurement area of the positioning machine containing the pressure microphone. As the sound field is assumed to be symmetrical, measurements for mapping were performed in one half of the plane situated on the level of ear channels. To obtain a sufficiently detailed map at all frequencies of interest, a distance between measurement positions was chosen of 2 cm. A complete map was assembled for the active system on and off, resulting in maps of attenuation.

Both tested configurations were based on a two-channel feed-forward system with arrangement $1\times2\times2$ (see Figure 11). A filtered-x LMS adaptive algorithm was implemented in floating-point DSP. Modeling of identified transfer functions of error paths was realized by means of IIR filters. As the whole system was stable in time, off-line identification was performed prior to the operation of the system.

The system was tested for attenuation of band pass white noise from 100 Hz to 900 Hz. Sound field mapping was performed by a positioning machine, with a distance between

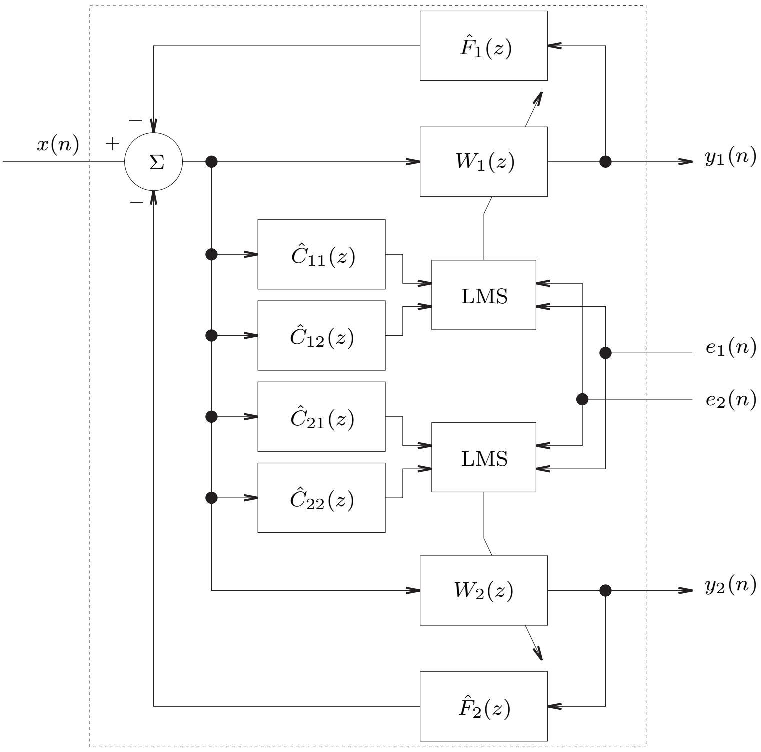

Figure 11: Block diagram of 1 × 2 × 2 ANC system. with acoustic feedback compensation

microphone positions between 1 cm and 3 cm, depending on the distance from the artificial head.

To ensure that the measured values will not be disturbed by influences from the immediate surroundings, the experiment is located inside an anechoic room located in the Acoustic Laboratory of the Department of Physics of the CTU. The source of noise was simulated by a high-level loudspeaker box placed 5 m away from the artificial head placed in the usual position of the human head of a seated person. As an artificial head, a head simulator corresponding to the IEC 959 Standard including an ear simulator was used.

Results of the mapping of zones of quiet are shown in Figures 12–19. From Figures 13 and 17 it is seen that 500 Hz is the highest possible useful frequency. On the other hand for 900 Hz small secondary zones of quiet in further areas are achieved, but the sound pressure level increases close to human ears.

Nevertheless, both configurations appear useful for creation of zones of quiet at position of human head at passenger seat, and both configurations are applicable for noise control in passenger seats in cars or small aircrafts [36].

6 Main trends of active noise control method development

The following section provides a summary of existing and potential applications and research areas of active control technology. Because of limited time, and mainly due to the very large number of separate areas, we do not assume this list to be complete [1].

Duct and pipes In the 1970s, Jessel and his contemporaries pioneered active control of sound in ducts. Due to the analytical simplicity of one dimensional systems the im-

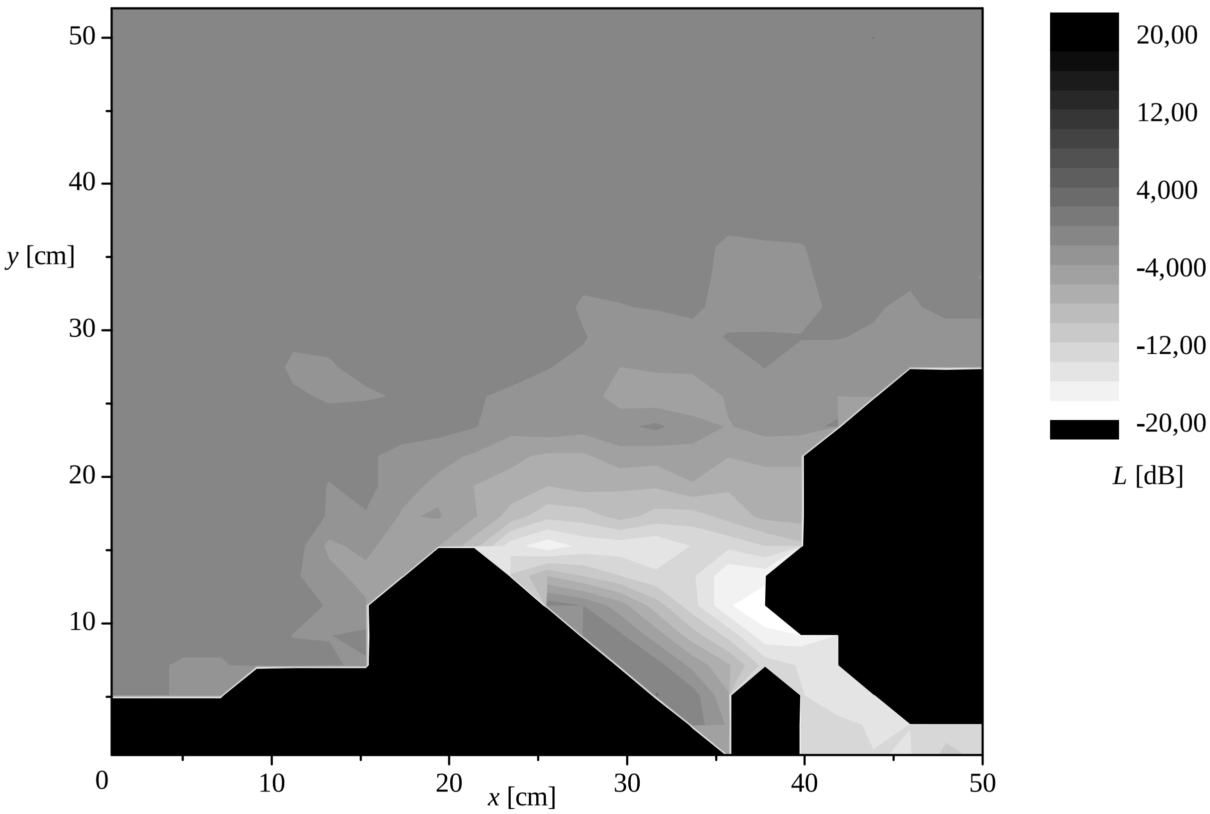

Figure 12: Attenuation map for 160 Hz, configuration 1

plementation is very straightforward. Signal and control microphones sense the sound field, and an adaptive filter is used to generate a control signal to a secondary source (loudspeaker). The objective is to have the sound pressure of the wave propagating down the duct combine with the sound pressure generated by the loudspeaker in such a way as to minimize the sound pressure at the control microphone. This leads to a reduction in the level of the sound wave propagating down the duct. The sound field between the primary and secondary sources is generally not reduced, and consists of standing waves.

Several studies and experimental investigations of cross-modes in industrial ducts point out the feasibility of controlling the sound in ducts of large cross-sections. However, subdividing a duct into smaller parallel sections provides an opportunity for control of each section separately by simple plane wave control systems. There are important applications on the control of sound radiation from chimney stacks of turbine driven power plants. Generally, passive silencers create a significant back pressure leading to an increased fuel consumption. Although the attenuation of medium and high frequencies will still require passive stack treatment, the overall size of the silencer can be relatively small. It has been proven in other applications that a system of secondary sources can modify the radiation pattern of the stack so that the environmental protection of selected areas can be achieved.

Enclosures A global reduction of sound in enclosures is of great practical interest. Theoretical analysis shows that a reasonable attenuation can be obtained only at low frequencies in enclosures with low modal densities. Depending on enclosure size and the number of modes to be canceled, a large number of sensors and actuators may be needed. The usual goal is to reduce the total potential energy. Assuming a complete sound field

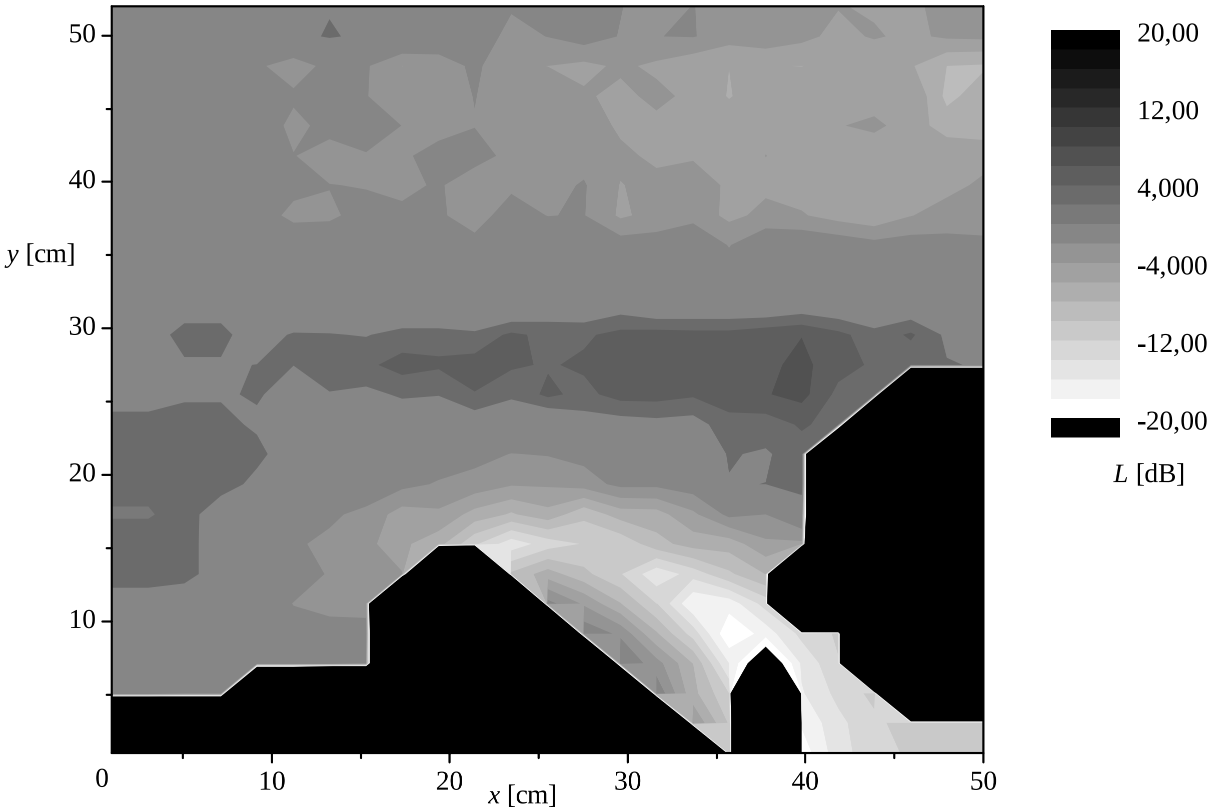

Figure 13: Attenuation map for 500 Hz, configuration 1

sensing, and given the number of actuators, the degree of attenuation depends on their locations. A variety of techniques have been explored and tested to determine optimal actuator locations, but as of this date no analytically deduced guidelines for optimum secondary source locations exist. The highest attenuation can be achieved if, instead of acting on room modes, the secondary sources are placed as close as possible to the primary sources; due to the acoustical coupling between the sources, the total sound power is reduced.

Active control in vehicles An important application of active control in enclosures is sound reduction in automobiles. This application has been heavily pursued in the past. For practical reasons, the sensors and actuators must be located close to the car body.

The interior noise in a passenger car has recently become one of the indicators of the car's quality. Therefore, because passive treatments have in essence been utilized to their limits, the automotive industry is eager to explore active control to achieve further noise reduction.

Another important application is the noise reduction in small airplanes. The reduction of propeller generated tones inside the aircraft fuselage has been successfully demonstrated in the past. Depending on location and frequency the tonal components of the spectrum were reduced by more than 10 dB. The noise reduction is a combination of local and global cancellation. One type of cancellation system uses many secondary sources which are controlled by microphones in the seat headrests. Other systems control fuselage vibrations.

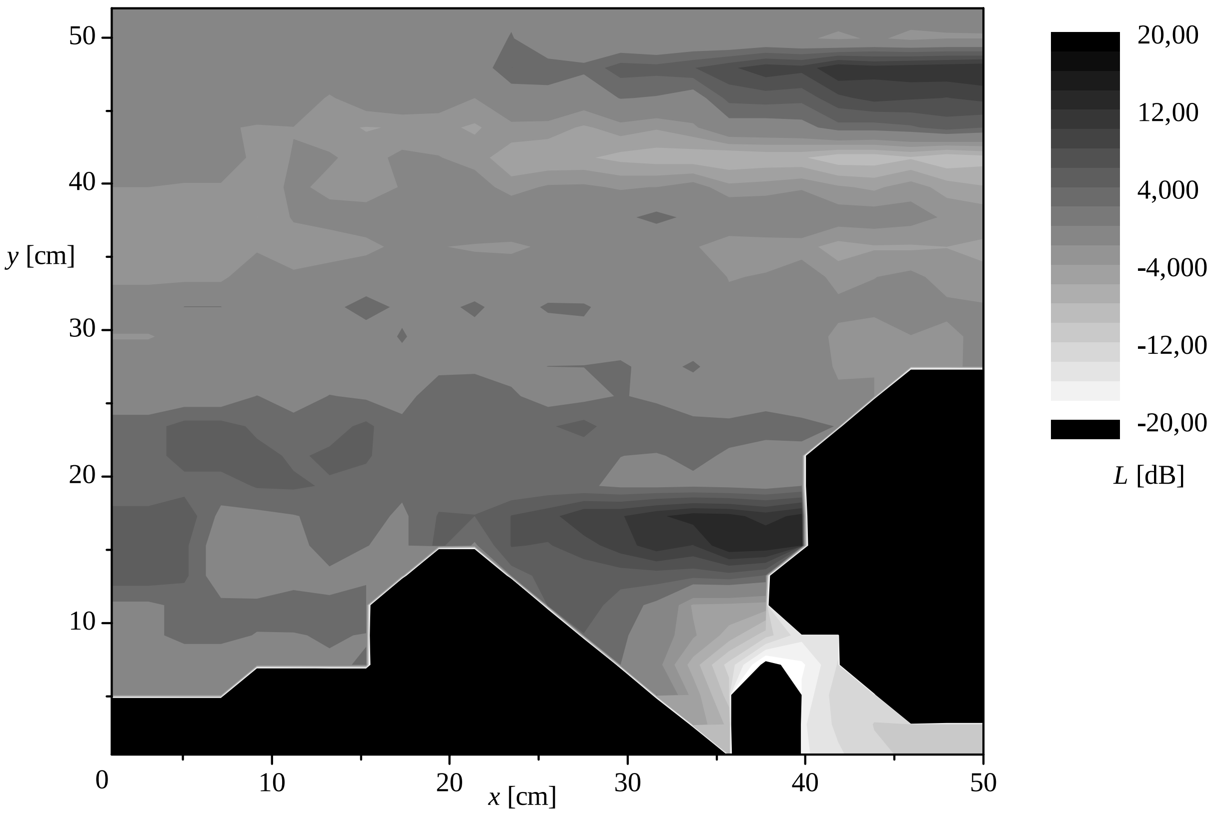

Figure 14: Attenuation map for 650 Hz, configuration 1

Acoustic coupling There are many practical situations in which the sound radiation from a complex stand-alone source must be reduced. In principle, a global sound field reduction can be achieved by reducing the total sound power radiation using acoustical coupling between the primary source and the system of secondary sources. So far such a system based on optimizing the secondary source output form maximum coupling has not been demonstrated.

Radiation control Extensive research effort has been devoted to control structural vibrations to minimize sound radiation.

Structural control of radiated noise can, in addition, potentially minimize vibrational amplitudes. Such a reduction of vibrational amplitude on a structure such as an aircraft fuselage may be important to prevent structural damage. However, it has been shown that reduction of the radiated sound using active control may lead to an increase in vibrational amplitudes.

Active control of structural vibration The goal of structural vibration control is usually either to decrease the vibrational amplitude or to reduce the coupling and vibration transmission into another structural element. Most papers published on this subject have made an impact by increasing the understanding of structural behavior; power flow and power transmission between structures. However, active control has not yet penetrated into applications which are so far dominated by passive treatments and structural modifications.

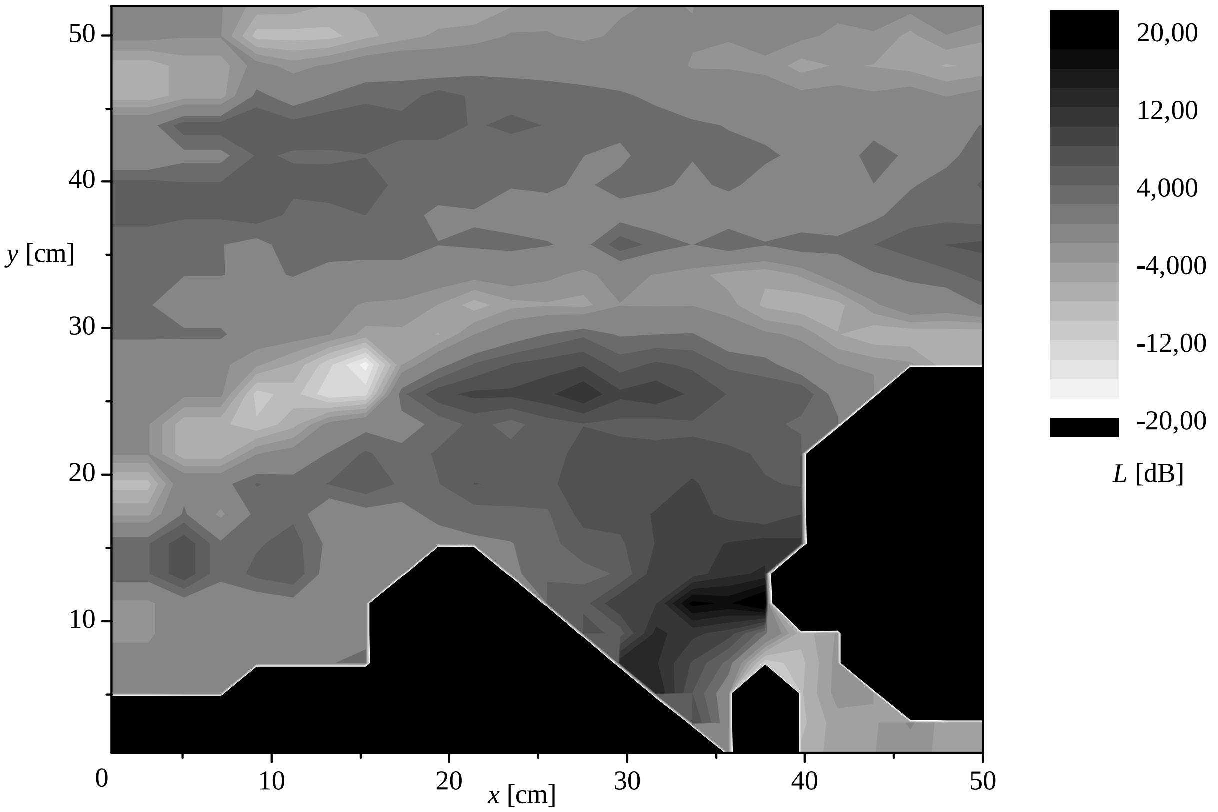

Figure 15: Attenuation map for 900 Hz, configuration 1

Transducers for active control The availability and quality of transducers, particularly actuators, is crucial to the implementation of any active control system. The initial lack of durable actuators created some skepticism about the feasibility of practical applications. However, industry reacted quickly to improve the durability of electrodynamic transducers for sound radiation. The existing installations have proven that the loudspeakers for sound cancellation in ducts can operate continuously in a properly designed enclosure. Bandpass systems with two resonators boost speaker efficiency and reduce the requirements on power consumption. Loudspeaker manufacturers now have the technology to meet the severe requirements on speaker performance. Development and production are obviously linked to demand.

7 Conclusions

The principle of active noise control was presented for the first time more than 70 years ago. However, its practical development was spurred by appearance of modern, particularly digital, technologies. At present, we can see more and more areas for applications of this methods. The ANC systems can now be used in many practical areas of acoustics and vibration. Even if we are speaking about commercial applications of ANC, there are still many varied problems to solve. Attention can be drawn to the new, more effective algorithms, new kinds of transducers (particularly actuators), searching of new areas especially in the field of active control of three-dimensional sound fields and vibrations.

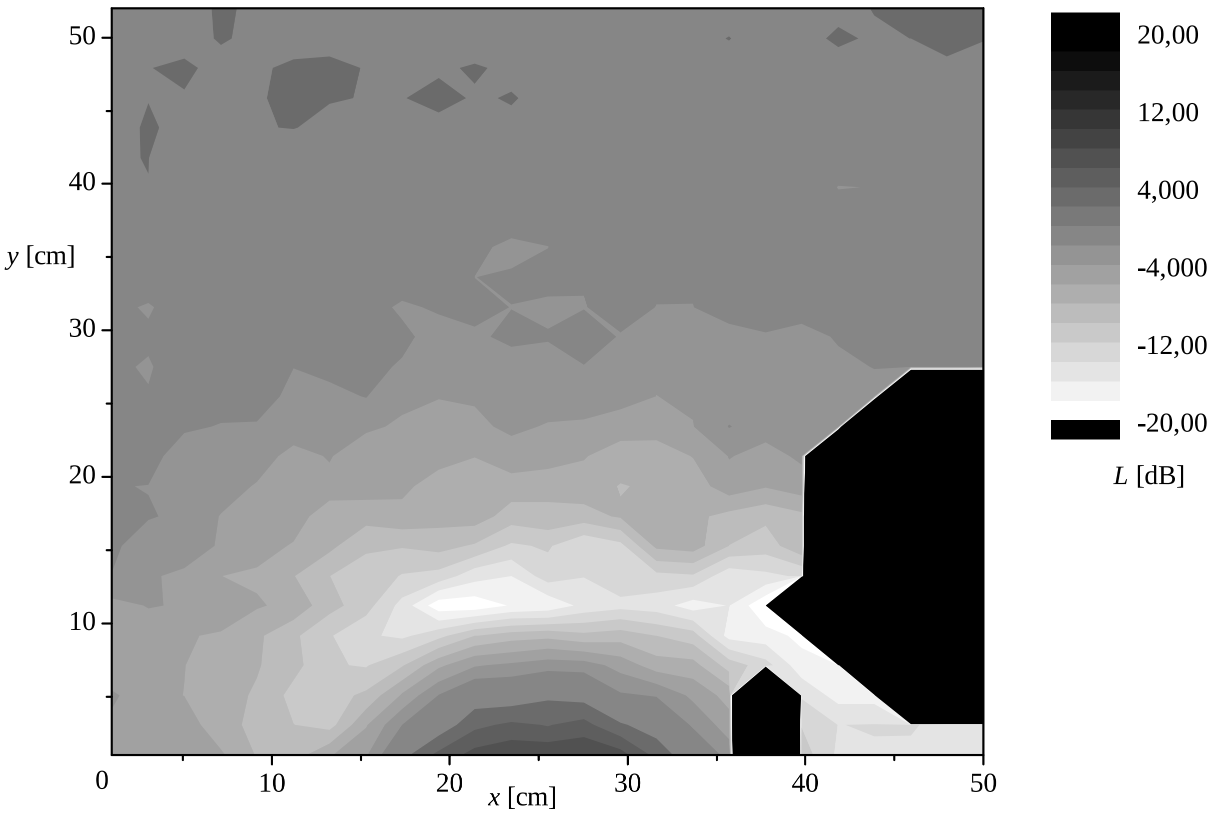

Figure 16: Attenuation map for 160 Hz, configuration 2

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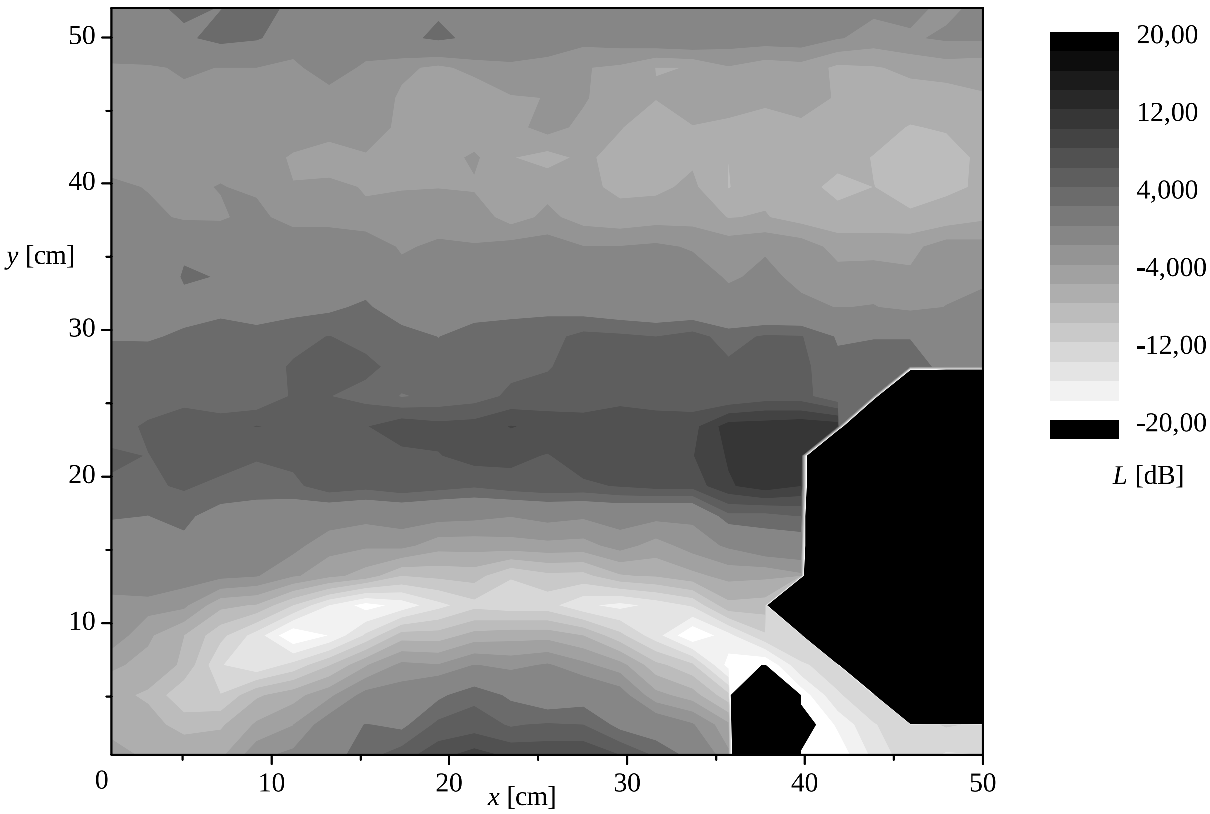

Figure 17: Attenuation map for 500 Hz, configuration 2

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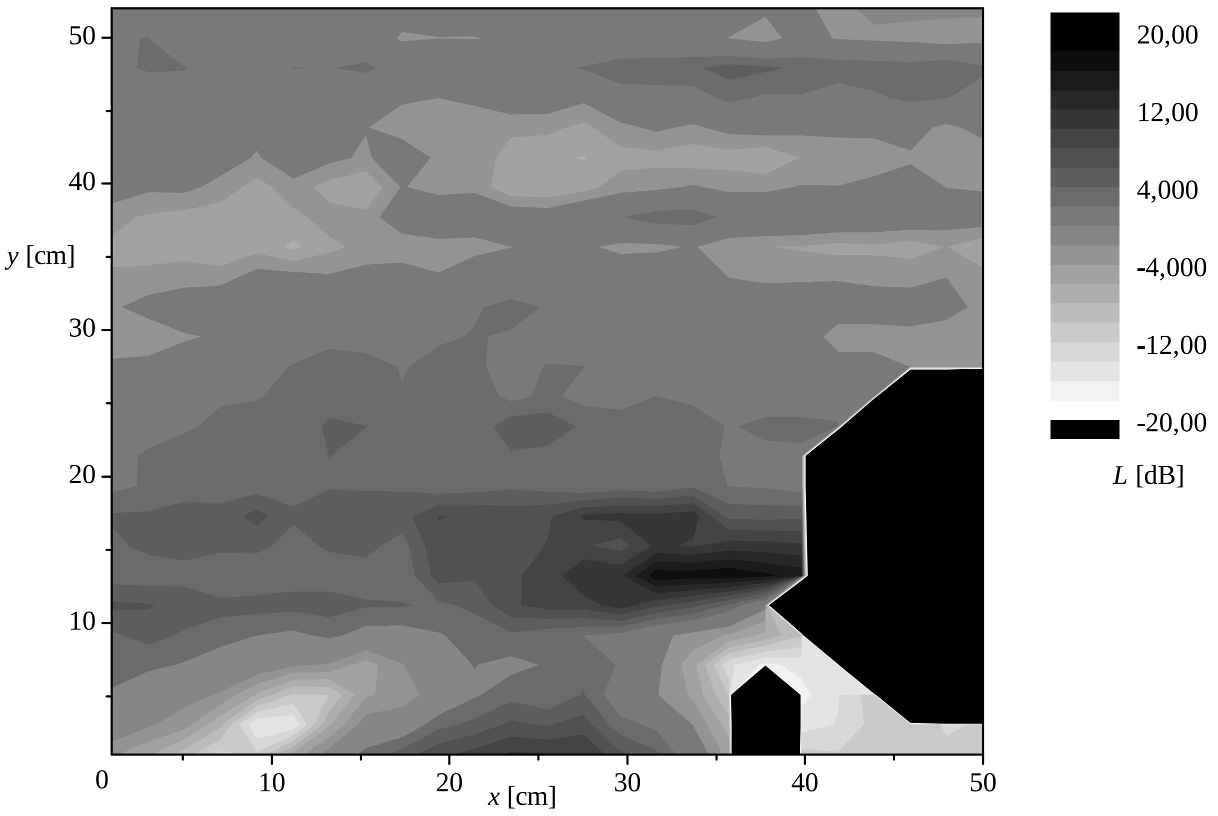

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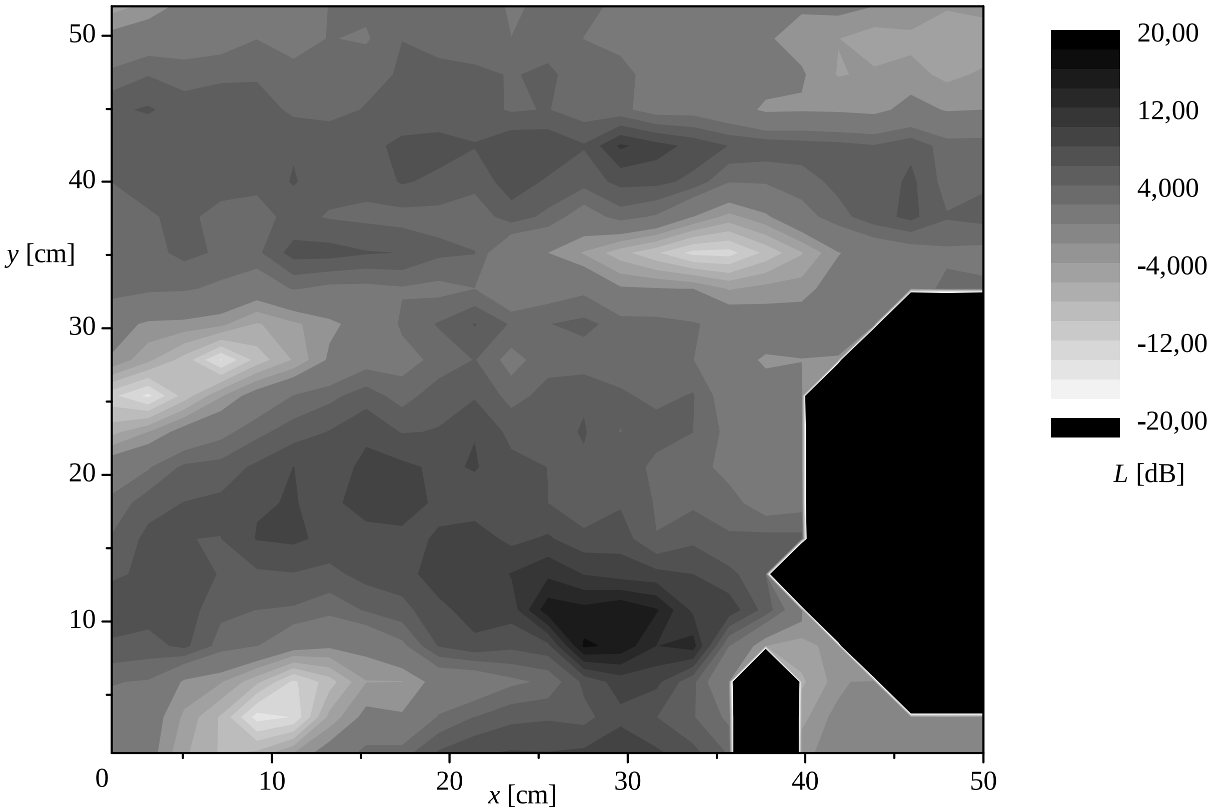

Figure 19: Attenuation map for 900 Hz, configuration 2

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