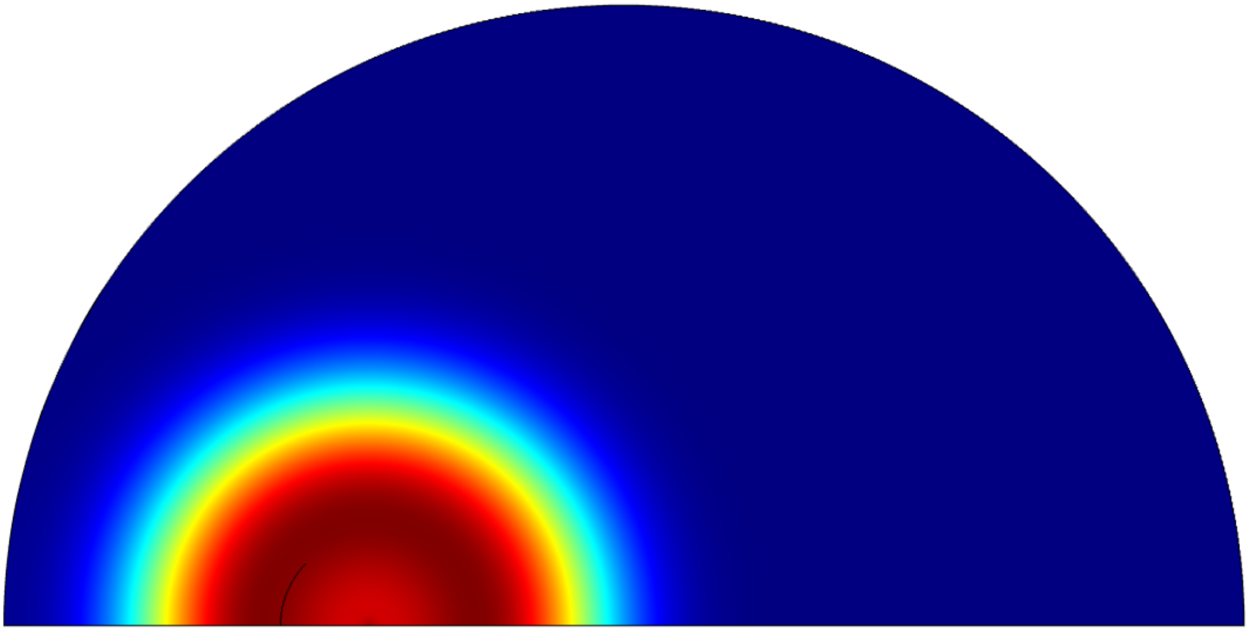
CHALMERS
UNIVERSITY OF TECHNOLOGY



Active control of first order wall reflections in large cylindrical rooms

Master of Science Thesis in the Master's Programme Sound and Vibration

VERONIKA EMMA JÖNEBRATT

Department of Civil and Environmental Engineering
Division of Applied Acoustics
Room acoustics Research Group
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Master's Thesis 2015:46

Master's thesis 2015:46

Active control of first order wall reflections in large cylindrical rooms

Master of Science Thesis in the Master's Programme
Sound and Vibration

VERONIKA EMMA JÖNEBRATT

Department of Civil and Environmental Engineering
Division of Applied Acoustics
Room acoustics Research Group
Chalmers University of Technology
Gothenburg, Sweden 2015

Active control of first order wall reflections in large cylindrical rooms
Master of Sience Thesis in the Master's Programme Sound and Vibration
VERONIKA EMMA JÖNEBRATT

Examensarbete 2015:46/Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2015

Department of Civil and Environmental Engineering
Division of Applied Acoustics
Room acoustics Research Group
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

Cover: Sound propagation visualization of a monopole source on the axis of symmetry in a cylindrical room.

Printed by [Name of printing company]
Gothenburg, Sweden 2015

Active control of first order wall reflections in large cylindrical rooms
Master of Science Thesis in the Master's Programme Sound and Vibration

VERONIKA EMMA JÖNEBRATT
Department of Civil and Environmental Engineering
Division of Applied Acoustics
Room acoustics Research Group
Chalmers University of Technology

Abstract

This thesis aims to investigate whether an active noise control system can be implemented in a large cylindrical multi-purpose hall to suppress low frequency reflections. Low frequencies from subwoofers, here 30 to 60 Hz, are studied and the objective is to suppress the first reflection from its closest wall at these frequencies.

The active noise control system under study is adjusted for one primary subwoofer located at 5.1 metres from the origin of a 12.4 metre radius hall. Seven equally spaced secondary subwoofers, used to suppress the first reflection from the closest wall, are placed at the boundary of the hall covering a 90 degree circular sector. The secondary sources are connected to a digital filter affecting the amplitude and delay of the fed signal.

Two methods have been used to investigate the behaviour of different active noise control configurations, the finite element method, FEM, and measurements in a 1:15 scale model. The FE model was created in the 2D plane, based on the assumption that the sound would mainly propagate in the horizontal plane. Moreover, the sound sources in this method were fed with a transient signal. The scale model was made out of wood, given a 10 centimetre absorptive ceiling and put on a concrete floor. The loudspeakers were fed with band-passed white noise (250 to 1500 Hz).

Thirteen active noise control configurations were investigated. Two positions in the room, the focal point and a critical area between the primary and secondary sources, both on ground level, were evaluated. It was found that the main parameter that has to be adjusted is how much total power that is fed to the secondary sources; the number of secondary sources and their distribution play a less important role.

This study showed that an active noise control system can be a suitable measure to suppress low frequency reflections in large cylindrical halls.

Keywords: ANC, room acoustics, electroacoustics, multi-purpose hall, FEM, scale modelling, cylindrical room, low frequencies, sound pressure reduction.

Aktiv kontroll av första ordningens väggreflexer i stora cylindriska rum
Examensarbete inom masterprogrammet Sound and Vibration

VERONIKA EMMA JÖNEBRATT
Institutionen för Bygg- och Miljöteknik
Avdelningen för Teknisk Akustik
Forskargrupp Rumsakustik
Chalmers Tekniska Högskola

Sammanfattning

Syftet med det här masterarbetet är att undersöka om ett ANC-system kan användas för att dämpa reflexer vid låga frekvenser i en stor cylindriska multi-arena. Låga frekvenser från subwoofers, här 30 till 60 Hz, står i fokus och målet är att dämpa den första reflektionen från subwooferns närmaste vägg vid dessa frekvenser.

ANC-systemet är anpassat för en primär subwoofer placerad 5,1 meter från mitten av en multi-arena med radien 12,4 meter. Sju sekundära subwoofers, jämnt utsprida längs väggen i en 90 graders cirkelsektor, används för att dämpa ljudtrycksnivån. Dessa är anslutna via ett digitalt filter som justerar signalens tidsfördröjning och amplitud.

Två metoder, finita element metoden, FEM, och mätningar i en 1:15 skalmodell, har används för att undersöka effekterna av olika ANC-konfigurationer. FE-modellen gjordes i 2D på grund av att ljudet i rummet antogs propagera i främst horisontalplanet. Källorna i denna metod var givna transienta signaler. Skalmodellen byggdes i trä, förseddes med ett 10 centimeter tjockt lager absorbent i taket och placerades på ett betonggolv. Högtalarna i skalmodellen producerade ett bandpassat vitt brus (250 till 1500 Hz).

Tretton ANC-konfigurationer undersöktes. Två positioner i rummet, fokuseringspunkten och i ett kritiskt område mellan den primära och de sekundära källorna, båda i golvplan, utvärderades. Det visade sig att den viktigaste parametern att justera är den totala effekten till de sekundära källorna. Antalet sekundära källor och dess rumsliga spridning spelar mindre roll.

Studien visade att ANC kan vara en lämplig åtgärd för att dämpa låga frekvenser i stora cylindriska rum.

Nyckelord: ANC, rumsakustik, elektroakustik, multi-arena, FEM, skalmodell, cylindriskt rum, låga frekvenser, ljudtrycksreduktion.

Aktive Kontrolle von Wandreflexionen erster Ordnung in großen zylindrischen Räumen
Abschlussarbeit im Studiengang Bauwesen und Umwelttechnik/Sound and Vibration zur Erlangung des akademischen Grades des Master of Science

VERONIKA EMMA JÖNEBRATT
Institut für Bauwesen und Umwelttechnik
Abteilung Angewandte Akustik
Technische Universität Chalmers

Zusammenfassung

Ziel dieser Masterarbeit ist die Untersuchung der Nutzung eines ANC-Systems, um Reflexionen tiefer Frequenzen in einer großen zylindrischen Multi-Arena zu dämpfen. Im Fokus liegen dabei tiefe Frequenzen von Subwoofern (30 bis 60 Hz), wobei als Ziel die Unterdrückung der ersten Reflexion des Schalls an der dem Subwoofer nächstgelegenen Wand definiert wird.

Das ANC-System ist auf einen primären Subwoofer abgestimmt, der im Abstand von 5,1 Metern zum Mittelpunkt einer Multi-Arena mit dem Radius 12,4 Meter liegt. Sieben sekundäre Subwoofer, regelmäßig an der Wand in einem 90 Grad Kreissektor verteilt, dienen der Dämpfung der ersten Wandreflexion. Sie sind über ein digitales Filter angeschlossen, das die Zeitverzögerung und die Amplitude korrigiert.

Zwei Methoden werden im Laufe der vorliegenden Arbeit zum Nachweis der Wirkung verschiedener ANC-Konfigurationen angewendet: die Finite-Element-Methode und Messungen in einem 1:15 Miniaturmodell. Das FE-Modell wurde aufgrund überwiegend horizontaler Schallausbreitung in 2D aufgebaut. In dieser Methode produzierten die Quellen transiente Signale. Das Miniaturmodell wurde aus Holz aufgebaut, mit 10 Zentimetern Deckenabsorber ausgestattet und auf einen Betonboden gestellt. Die Lautsprecher im Miniaturmodell wurden mit weißem Rauschen zwischen 250 und 1500 Hz gespeist.

Dreizehn ANC-Konfigurationen werden untersucht. Zwei Positionen im Raum werden ausgewertet, der Brennpunkt und ein kritischer Bereich zwischen der primären Quelle und den sekundären Quellen, beide auf Bodenebene. Nachweisbar ist, dass die Regelung der zugeführten Gesamtleistung zu den sekundären Quellen der Hauptparameter ist. Die Anzahl der sekundären Quellen und dessen Ausbreitung ist zweitrangig.

Als Ergebnis der vorliegenden Masterarbeit kann festgehalten werden, dass ein ANC-System genutzt werden kann, um tiefe Frequenzen zu dämpfen.

Schlüsselwörter: ANC, Raumakustik, Elektroakustik, Multi-Arena, FEM, Miniaturmodell, zylindrischer Raum, tiefe Frequenzen, Schallpegelreduktion.

Preface

In the end of last year I had some nice and long talks with Gunilla Sundin and Anders Westbrandt, Norconsult AB/Akustikon, about a master's thesis I potentially could do with them. Our discussions took some different paths before ending up in investigating the usage of active noise control in gas holders and the thesis *Active control of first order wall reflections in large cylindrical rooms.* Before our discussions, I had set my head on acquainting myself with a technically demanding subject within the room acoustics field. After half a year of hard struggle, there is at least one thing that I'm certain about; I succeeded in choosing a demanding topic. Due to this, this project hadn't been finalised without the support from a number of competent people. This is why I'm sending my deepest gratitude to Lars Hansson, Wolfgang Kropp, Carsten Hoever, Börje Wijk, Gunilla Skog, Carl Grehan and the above mentioned.

My five years of studies at Chalmers has finally reached an end. It is with a great backpack of invaluable knowledge I'm now entering the world outside. I will do my very best to practice what the hard work has given me to take part in creating a better world.

Veronika Jönebratt, Gothenburg, June 2015

Contents

Nomenclature

Gas holder	Storage for gas. Used in the 19th and beginning of 20th centuries. (Gävle Kommun, 2014)
Focal point	"The point at which rays or waves meet after reflection or refraction, or the point from which diverging rays or waves appear to proceed." (Oxford University Press, 2015)
ANC	Active Noise Control. A technique to modify/control sound fields by the means of electroacoustic transducers. Usually the aim is to reduce noise, but it might also be to modify sound with respect to its contents or character. (Kropp, 2014)
Multi-purpose halls	A venue designed to suit multiple purposes, e.g. music and theatres.
Primary source	i.e. Primary subwoofer/loudspeaker. Source producing wanted and unwanted sound.
Secondary sources	i.e. Secondary subwoofer/loudspeaker. Sources producing anti-noise to eliminate the unwanted sound from the primary source.
Receiver microphones	i.e. Receivers. Observer microphones placed in a position where the sound field is to be evaluated.
Free field	"An environment in which there are no reflective surfaces within the frequency region of interest." (Baukal, 2004)
Schroeder frequency	Denotes the boundary where a reverberant room behaviour appears. Below this boundary discrete room modes will appear (Linkwitz Lab, 2015). Here the Schroeder frequency is the upper limit where ANC no longer is beneficial.
Omni-directional source	A source transmitting equal amount of power in all directions.
Critical point	Here a position on the focal axis (intersecting the source position and the focal point). A distance of 1.8 metres from the primary source in the direction of the secondary sources.
Transient	A deterministic, non-periodic signal. A large pressure increase within a short period of time.
CFL number	Dimensionless parameter. Limits the distance a wave travels within one calculation time step in the finite element method. (Comsol Multiphysics, 2014)
DSP	Digital signal processor.
Dirac pulse	A function which is zero everywhere except at one discrete time where it is infinite.

1 Introduction

Sound radiation from a sound source in a room will be reflected and scattered at the walls (Birkedal, 2007). The sound pressure at different frequencies and positions in the room will vary greatly until steady state is obtained. This is caused by the phenomenon that the sound pressure at a position in a room is the sum of the direct sound wave and the large amount of reflected sound waves generated by the room boundaries. To get rid of the varying sound pressure in different locations in a room is a criterion that is of great importance to achieve a pleasant sound environment.

There are a few traditional ways of enhancing the perceived sound in a room (Birkedal, 2007). Classical solutions are e.g. to use passive absorbers, to choose the positions of the loudspeakers carefully and to use manual equalizing for the sound sent to the sound system. Furthermore, to implement automatically equalization which is based on measurements done in one position and is sent back to the system to improve the sound in this particular position, can be used. Improvement of the room characteristics, quality of the loudspeaker and psychoacoustical measures can also have a positive effect.

In cylindrical rooms, e.g. *gas holders*, all reflections from a sound source will intersect in one *focal point* (Comsol Multiphysics, 2014). This location, which appears at the opposite side of the room from the sound source, at an equal distance from the origin, will have the most critical sound pressure in the room (see Figure 1.1). This phenomena occurs at a delay of a/c seconds from the excitation of the source, where a is the travelling distance from the source to the receiver in metres and c is the speed of sound in air in metres per second.

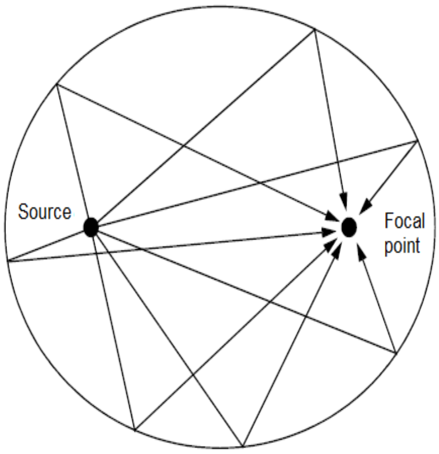


Figure 1.1: Focal point in a 2D cylindrical room.

Low frequencies with wavelengths in the order of the dimensions of the studied room will be hard to absorb using traditional methods. At these frequencies, the perceived timbre of a signal is a question of the interaction between loudspeakers and room (Welti, nd). Moreover, a booming noise easily appears due to reflections (Birkedal, 2007).

A so-called active noise control, *ANC*, system is an alternative approach to suppressing noise. This technique has been used in several commercial applications where absorption at low frequencies is lacking, e.g. in small music rooms and in noisy places in general.

1.1 Background

In the 19th and beginning of 20th centuries, the coal gas industry was flourishing in the industrialised parts of Europe (Russell, 2014). The gas was mainly used as fuel in street lanterns, but also in factories and households. Most cities had its own gasworks that supplied the city with its necessities. Due to the introduction of electricity and rising costs of the gas production during the Second World War a turning point for the gas industry was denoted. In Sweden, the amount of gasworks decreased rapidly. The last ones were decommissioned during the 1960's (Nilsson, 2002).

Each gasworks plant consisted of several buildings taking care of different steps in the gas production (Gävle Kommun, 2014). One of these buildings was the storage container(s), the so-called *gas holder*. The gas holder, which normally was cylindrical, had a huge volume with typically a diameter of 20-60 metres and largely varying height.

As the production of coal gas was out-rivaled by other fuel types a lot of gasworks were abandoned. Recently the discussion about whether they should be kept as western industrialisation monuments and how they can be reused has arisen in Sweden (Lindegren, 2013). In Gävle the gas holders have been renovated and are now used as *multi-purpose halls* (Gävle Kommun, 2014). The same usage is being investigated in Stockholm, Hjorthagen.

The extensive volume and cylindrical shape of gas holders are parameters making it complicated to create a pleasant acoustical environment for different types of performances. Norconsult AB/Akustikon has been given the commission to investigate possible acoustical improvements in the halls in Stockholm (*Gas holder 2*) and Gävle (*The large gas holder*). Both gas holders have brick walls. The one in Gävle has a diameter of 24.8 metres, a 10.6 metre high wooden ceiling and a wooden floor with a story below. The one in Stockholm has a diameter of 53 metres, a 51 metre high wooden ceiling and a concrete floor.

One of the main issues in the halls is to get rid of reflections at low frequencies as this creates an unwanted amplified sound field in crucial positions. This question is the focus of this report.

1.2 Aim

The objective of this thesis was to investigate how active noise control can be used to cancel out low frequencies from subwoofers in large cylindrical rooms, e.g. gas holders. The implementation of this technique aims to cancel out the first reflection from a crucial part of the wall to obtain a sound pressure reduction from this refection in some predefined positions in the room. The central focus was upon the number, placement and distribution of subwoofers at the boundary of the room and the power fed to each subwoofer.

1.3 Limitations

The frequency range of interest was chosen to be 30 to 60 Hz, which corresponds to the lowest troublesome frequencies transmitted from the main subwoofers in the two gas holders mentioned in Section 1.1. The mid-frequency 42 Hz is used for the choice of secondary source distribution, assuming it to give an adequate result for the whole frequency band. Due to the 1:15 scale the frequencies 450 to 900 Hz where studied in the scale model.

No measurements were performed in the gas holders mentioned above. Investigations done in the finite element software Comsol Multiphysics 5.0 and in a 1:15 scale model of the gas holder in Gävle could therefore not be compared to these non-existing full-scale measurements. The intention of using the finite element method was to get an indication of what to investigate in the scale model measurements;lders. assumed represantative of the full-scale gas g The scale model measurements were assumed to be applicable to full-scale gas holders.

The Comsol calculations were solely done in the time domain and only ten ANC configurations were studied in this method. It was assumed that a 2D finite element model would be an adequate representation of the original problem, as the ceiling was assumed to be totally absorptive, i.e. no substantial sound propagation in the vertical direction. Furthermore, the sound pressure reduction in the scale model, used to examine the achievements of the ANC technique, was measured at ground level.

Seven secondary loudspeakers were available for the scale model measurements. This implied that only four secondary sources, due to the axis of symmetry, were implemented in the finite element model.

The material properties of the scale model did not strictly correspond to the actual gas holders as it had not been exhaustive investigated. It was furthermore difficult to thoroughly evaluate the properties of the scale model building material when cylindrically put together.

Only an feed-forward active noise control system was implemented in the scale model. This was done as the signal fed to the system was electric powered from a PA system and hence known. Moreover, this also implies that the ANC system cannot be implemented for acoustic performances. An off-line system was additionally chosen.

The positions where the sound pressure was evaluated were limited to the focal point and one problematic position/area, as they previously had been identified to be troublesome (illustrated in Figure 3.1). The problematic position/area in the room had been identified to be outwards from the primary source towards the closest wall, i.e. a circular sector with an angle of 45 degrees to the front and to the back (all in all 90 degrees). The part of the circular sector closest to the primary source was supposed to be the most critical. A one-quarter circle with radius a quarter of the distance to the wall was hence used as evaluation position in the finite element calculations. In the scale model measurements a point, the so-called *critical point*, a quarter of the distance to the closest wall on the focal axis, intersecting the primary source and the focal point, was used.

2 Theory

The idea of active noise control, *ANC*, is to cancel out sound coming from a *primary source* with sound from a *secondary source(-s)* (Nelson, 1992). The system will be the most efficient, i.e. obtain total cancellation, if the two sound waves, with the same frequency, are striking each other with the same amplitude but with opposite phase, i.e. phase difference 180°. If they hit each other out of phase or their amplitudes are unevenly large, the signal level will only be reduced, or even increased.

Implementation of ANC at low frequencies is easier than at high frequencies (Birkedal, 2007). This is due to the large wavelengths of low frequencies. Large wavelengths are more forgiving in absolute measure (time) than small wavelengths and will have less scattering and damping effects. At low frequencies air absorption and humidity also do not have to be taken into account.

Due to the mode shapes of the sound waves, it will be easy to affect the sound in single positions but impossible to create a totally even sound field in the whole room (Welti, nd). To create an ANC system that generates an as even sound field as possible, a known average frequency response in the area that is object to control is needed.

There are two main categories of ANC: local and global (Lagö, 2008). The local control creates a silent zone around the *receiver microphone* with the size of approximately 0.1λ. In this method a high number of receiver microphones will increase the size of the zone but decrease the performance of the control. In the global control the sound pressure is instead reduced in all positions in the room (Nelson, 1992). This ambition is not always necessary in practice, as some positions may already have a low pressure level. To reduce the total acoustic potential energy in a room may instead be a useful objective. In both local and global control, the performance is highly correlated to the wavelength (Lagö, 2008). The coherence, i.e. no significant disturbance of the out-put signal, is also of big importance as well as causality, i.e. the impulse response has to be zero for all times smaller than zero (Nelson, 1992, pp. 85, 247).

ANC can be used to modify the acoustic properties at the boundaries of a room. Sometimes a *free field*-like behaviour of the sound field at the boundaries is desirable. A free field-like behaviour will be obtained if the first order reflections are eliminated, as this would induce that higher order reflections could not arise. The elimination of the first reflection can be illustrated with a Kundt's tube (see Figure 2.1) (Möser, 2009).

The figure shows the propagation of a plane wave and its reflection at the tube's end with the specific acoustic impedance Z. The behaviour of the sound field at the tube's end can be described by the so-called reflection coefficient (see Equation 2.1). The reflection coefficient is determined by the impedances Z of the two media at the interface. In this case the first impedance is given by $\rho_0 c_0$ (air density times

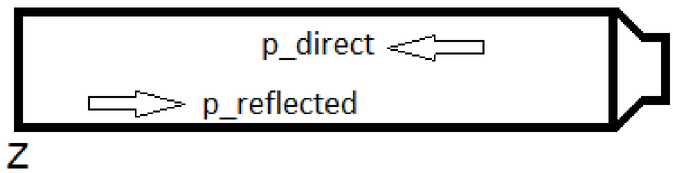


Figure 2.1: Sound propagation in a Kundt's tube with a reflective end.

speed of sound) as it is a plane wave propagating in air. The second impedance is that of the material at the tube's end. To create a free field-like behaviour at the tube's end, or a wall of a room, a material with impedance that would give a fully non-reflective boundary is needed, i.e r=0. This implies that Z has to be equal to $\rho_0 c_0$.

$$r = \frac{Z - \rho_0 c_0}{Z + \rho_0 c_0} \tag{2.1}$$

If the sound pressure is measured on the sound hard boundary of a cavity, i.e. r=1, the total pressure can be assumed to be the sum of the direct and reflected sound. As the boundary is totally reflective it can thus be presumed that suppressing half the measured pressure would eliminate the reflection and furthermore cause a free field-like sound environment. This could be a method to examine if the right impedance of the boundary is obtained.

2.1 Previous ANC implementations

A variety of studies have been evaluating the use of ANC in rooms, aiming for a better sound quality at low frequencies. Some of them are presented below.

2.1.1 Local control

The aim of the study *Physical Modeling of Active Cancellation of Low-Frequency Sound Signals* was to create a silent zone in a hollow room (Beogubtsev et al., 2011). Due to low efficiency in traditional passive absorption methods at low frequencies active cancellation systems (ACS) were evaluated. The silent zone was chosen to be a circle with a radius of 1 metre. The circular configuration, where receiver microphones and appurtenant secondary sources are placed in a circle, was chosen as it corresponds to the easiest active-cancellation implementation. The primary source was placed in a corner of the room at a distance of 3 metres from the silent zone and was provided with noise. It was already known that the circular configuration, together with an interference algorithm, only reaches its full measure by using a sufficiently large number of individually operated secondary sources. Due to the geometry of the configuration the secondary sources have a sufficient effect on the adjacent receivers, which leads to a narrowing of the operating frequency band and a limited cancellation.

Observation microphones where installed in several positions in the room to monitor the difference in sound pressure level before and after the implementation of the active cancellation system, i.e. the cancellation efficiency. At the control positions (circular receiver configuration) the signal was decreased to the background level in the room. Here, the cancellation efficiency was 30 to 40 dB, or more. Inside the circle the cancellation efficiency of discrete frequencies was 15 to 18 dB. Outside the circle a 3 to 4 dB reduction was observed. In a wide frequency band the active cancellation showed a reduction of the sound pressure level by 6 to 8 dB.

2.1.2 Subwoofer placement

The study *Subwoofers: Optimum Number and Locations* investigates how subwoofers can be used to eliminate modal excitation in a rectangular room (Welti, nd). When placing subwoofers in positions with equal coupling magnitude and opposite phase, there will not be any excitation of the particular mode. Theoretically, this would mean that a large number of subwoofers equally distributed around the room would result in equal positive and negative excitation of all potential modes (see the frequency response when using different amount of subwoofers in Figure 2.2). To implement the amount of subwoofers needed to get this result is unrealistic as it will be too costly.

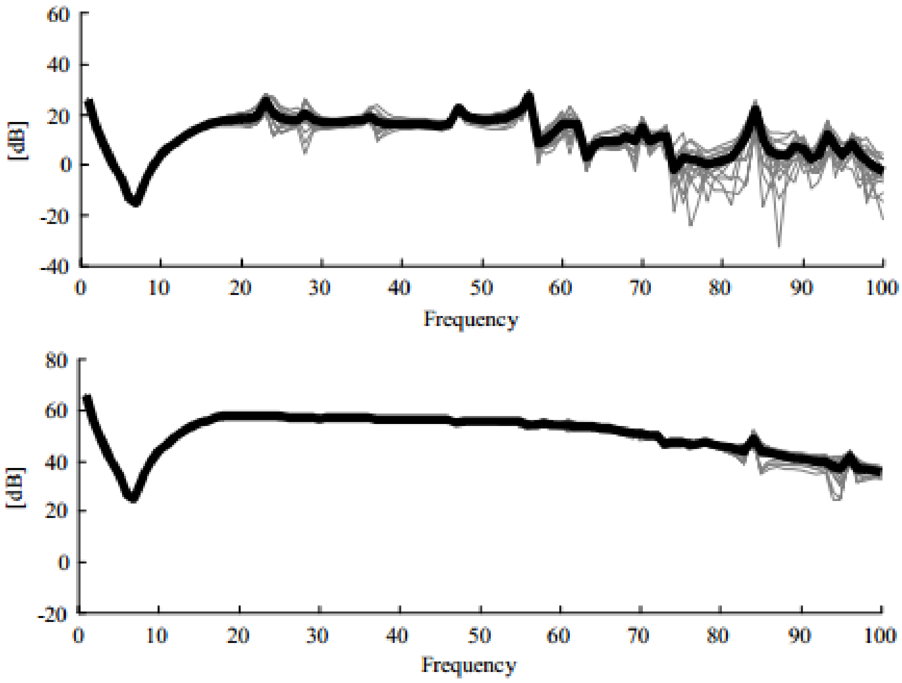


Figure 2.2: Averaged frequency response (black) in a rectangular room with 50 (upper) vs. 5000 (lower) randomly distributed subwoofers. Average calculated from 16 separate receivers (grey) in the centre of the room (Welti, nd).

A computer model experiment was performed where subwoofer positions along the walls of the rectangular room with a centred listening area were investigated. Eighteen subwoofers, all placed at the walls, were combined in 20 different ways where 1-18 positions were operating at the same time. Here it was concluded that there is no obvious benefit of implementing too many subwoofers. Instead subwoofer configurations consisting of only four subwoofers gave the best results. It was found that a symmetrical placement provided a better result than non-symmetrical ones and furthermore that it is complicated to predict what will happen in-between the modes. The most favourable configurations are presented in Figure 2.3.

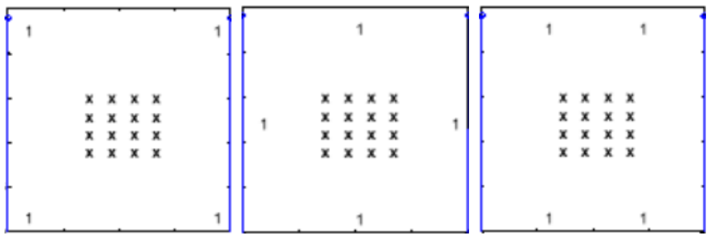


Figure 2.3: The most beneficial subwoofer configurations obtained in the computer model. The ones showing the subwoofer positions (Welti, nd).

Moreover, another five rectangular rooms with different dimensions were exposed to the same test. The above stated conclusions were found in all rooms. After finishing the computer experiment, the same examination was done in a real room with almost identical subwoofer positions. It was found that the conclusion from the computer model is in accordance with real room investigations.

2.1.3 Global control in angular rooms

At the Aalborg University in Denmark an ANC system has been developed (Birkedal, 2007). The Controlled Acoustically Bass System (CABS) is a system developed to control low frequencies in rectangular rooms. CABS is working in the time-domain and aims to give a homogeneous sound pressure level at low frequencies in the whole room by cancelling the first reflection (and thus get rid of all reflections) at the back wall. This cancellation would get rid of the resonances and anti-resonances and make the sound clearer, sharper, less muddy and without booming bass.

The CABS system was implemented in a room with the dimensions 7.08 x 4.12 x 2.78 m^3 (Birkedal, 2007). To evaluate the need of CABS a primary subwoofer was placed in one of the corners and 25 receiver microphones where distributed equally over an area (1.92 x 1.92 m^2) in the centre of the room. It was found that the sound pressure level at certain frequencies differed up to 30 dB between some of the microphone positions. Additionally it was found that the sound pressure level difference between different frequencies (20-100 Hz) in one position sometimes exceeded 25 dB. These differences motivated the use of CABS.

A principal set up of the CABS with four low frequency loudspeakers is shown in Figure 2.4. Both simulations and measurements of this set-up showed great improvements of the sound field; an almost homogeneous sound field in the whole room was achieved at frequencies up to 100 Hz.

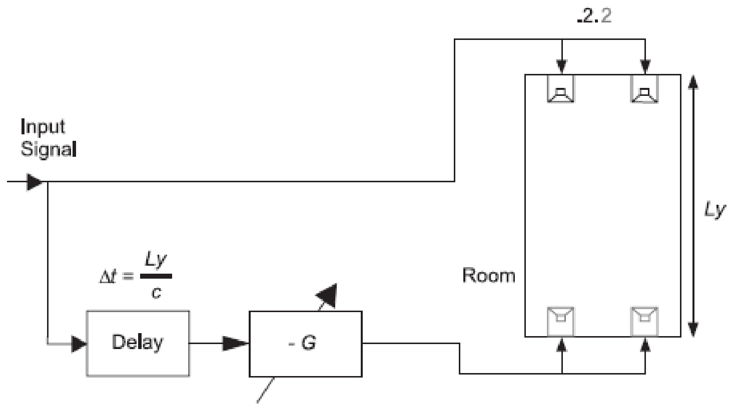


Figure 2.4: Block diagram of the principles of CABS (Birkedal, 2007).

From this study it was discovered that the smaller the room is the higher up in frequency is CABS efficient. The *Schroeder frequency* appeared to be a good estimate of the upper limit where CABS can be implemented:

$$f_s = 2000\sqrt{\frac{RT}{V}} \tag{2.2}$$

where RT denotes the reverberation time and V the volume of the room.

2.2 Placement of sources and receivers

Loudspeakers have a more *omni-directional* radiation at low frequencies than at high frequencies (high frequencies with wavelengths in the order of the dimensions of the loudspeakers). The placement of the loudspeakers is due to this not as critical at low frequencies as at high frequencies (Birkedal, 2007).

When loudspeakers are placed at a distance of half a wavelength from each other they obtain an array-like behaviour, emitting most of its sound intensity at the front and back of the loudspeakers due to internal amplification and cancellation to the sides. If the distance is decreased to a fourth of a wavelength the array obtains a lower effectiveness as it gets a more point source-like behaviour. At distances smaller than a fourth of a wavelength the array has lost all its efficiency and turned into a point source. This has to be kept in mind when constructing an ANC system consisting of several loudspeakers.

As mentioned in Chapter 1, there is a focal point appearing at the opposite side of the origin of the cylindrical room. Therefore, this point is considered to be an important point when aiming for sound pressure reduction in a cylindrical room. Ideal cancellation of the first reflection from the wall would induce vanishing of the focal point. Furthermore, it has been identified that a small area close to the source,but outside the near field, around the focal line (intersecting the source position and the focal point) in the direction of the closest wall is a problematic area when looking at the sound field. This position should therefore be the second critical position when investigating the impact from an ANC system.

2.3 The Finite Element Method

The finite element method (FEM) can be useful when numerically solving acoustical problems in the time-domain. The most developed method is based on the implementation of a *transient* excitation, i.e. a pulse (Marburg, 2008, p. 224).

Parts of a FE geometry can be neglected, due to axes of symmetry. The boundary appearing at an axis of symmetry is given a natural boundary condition (Ottosen, 1992).

To evaluate the impulse response of the room a pulse is the most intuitive source to excite the sound pressure field with. A Gaussian-type explosive source is a realistic model of a sound source of this type (Yue, 2005). In most cases the pressure acoustics can be assumed to be loss-less and linearized isentropic, which makes the wave equation solely dependent on the pressure (Comsol Multiphysics, 2012). These considerations apply for pulse response acoustics.

The resolution of the mesh of the FE model has to be based on the studied frequencies and the geometric features, to get an accurate result. In a simple geometry like a cylindrical gas holders, it is recommended to use 5 to 10 elements per wavelength (Comsol Multiphysics, 2012). To get a better accuracy in the FE solution either the number of elements or polynomial degree of the basis functions can be increased (Hornikx, 2009).

2.3.1 Comsol Multiphysics 5.0

In the Comsol Multiphysics software there is an acoustics module (Comsol Multiphysics, 2014). In this module, the pressure field in a cavity can be calculated. By default, Comsol uses second-order elements and Gauss integration. An adequate way of constructing a transient pressure source is to use the so-called Gaussian pulse (see Figure 2.5). This pulse has a shape similar to a normal distribution and is governed by the equation:

$$y(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(t-t_0)^2}{2\sigma^2}} \tag{2.3}$$

where t is the time variable, t_0 denotes the temporal location of the pulse peak and σ the standard deviation.

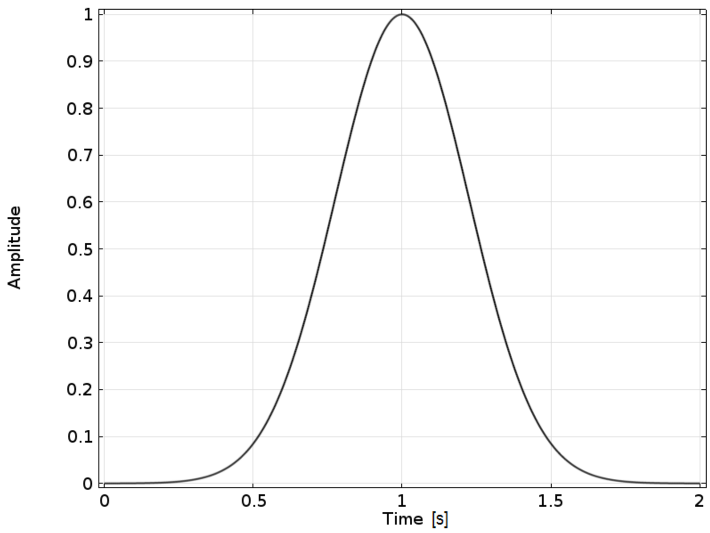


Figure 2.5: Normalised Gaussian pulse.

In the application where a Gaussian pulse is used to evaluate the pressure field in a room all the energy in the signal will be confined to the frequency band $-2\omega_0$ to $2\omega_0$ and have the highest energy concentration between $-\omega_0$ and ω_0, where $\omega_0 = 2\pi f_0$. To evaluate what frequencies that are contained in the pulse, created in the time domain, a Discrete Fourier Transform (DFT) can be applied. The upper frequency limit of the studied frequency band, f_0, should then be used to set up a mesh in the model that can solve all frequencies that are of interest (Comsol Multiphysics, 2014). The typical element size of the mesh, h_{max}, can then be solved using the equation:

$$h_{max} = \frac{c}{f_0 \cdot N} \tag{2.4}$$

where c is the speed of pressure in air and N is the number of elements per wavelength.

Another important parameter in the Comsol application is the *CFL number* (Comsol Multiphysics, 2014). This dimensionless parameter is helping to limit the distance a wave travels within one calculation time step t_{step}. If the discretization errors of the time and element sizes are equally large, a CFL number equal to one corresponds to the same resolution in time and space. This barely ever happens. A limiting step size, where the temporal and physical discretization errors approximately have the same size, is found when CFL < 0.2. A way to evaluate the accuracy of the CFL number in a cylindrical room is to examine it by trial and error to see how small it has to be to get a distinct focal point in the right position.

Normally an automatic time-step control in the time-dependent solver is used (Comsol Multiphysics, 2014). If all frequencies the mesh can resolve are contained in the excitation there is no need to use this control. Instead the time step t_{step} has to be limited to a much smaller distance than the size of an element. This value is related to the element size, e.g. mesh resolution h_{max} as well as the CFL number and is calculated by:

$$t_{step} = \frac{CFL \cdot h_{max}}{c} \tag{2.5}$$

2.4 Scale modelling demands

To use acoustical scale model measurements is a way to accurately evaluate the acoustic properties of a room. The method is commonly more realistic than computer modelling. However, the scale cannot be too small, as the actual frequency needs to be in the audible frequency range and small irregularities of the surfaces in the model will influence the reflection pattern in an unrealistic manner (Corakci, 2009). For air-borne sound the geometry, frequency range and reverberation time require the same scaling factor.

Scale model measurements require small loudspeakers and microphones (Long, 2006). The higher frequencies that have to be considered the more important it is to place the microphones and loudspeakers in the exact same place for each measurement (Corakci, 2009). A frequency range where air absorption occurs, i.e. very high frequencies arising from very small scale models, should preferably be avoided (Long, 2006).

The material in the scale model should have a correlated absorption coefficient to the real building, i.e. the absorption coefficient should have the same value in the scaled frequency as the original building has in the original frequency of interest. The performance of the material is depending on its attachment and has to be evaluated when mounted. This is often difficult as the test of material has to be performed in a Kundt's tube (or similar) and will not be possible to do when the material is mounted, bent or deformed. A way to get an understanding about the material is to test the impulse response of the scale model and compare it to the impulse response of the original building. If the impulse responses do not match, additional material can be added to the walls and ceiling of the scale model.

3 Implementation

To evaluate the number of subwoofers, and their inherent characteristics, needed to reduce the sound pressure of the first reflections from the wall in a gas holder, two different methods were implemented.

The first method was finite element calculations using the acoustics module of Comsol Multiphysics 5.0. The intention of using this method was to get an perceptive understanding of the sound propagation in cylindrical rooms and to be able to practice multiple solutions of the problem in an easy and flexible way.

The second method was to implement solutions from Comsol in an experiment; a scale model was built and the findings were implemented. The main focus was on the number of loudspeakers and their efficiencies.

3.1 FEM

A circular 2D Comsol geometry was created with the same radius as the gas holder in Gävle, i.e. 12.4 metres. 2D, which saves a lot of calculation time, was chosen as the ceiling was stated fully absorptive, eliminating the sound propagation in the vertical direction. Half the circle was neglected due to the axis of symmetry (see Figure 3.1). The axis of symmetry implies that each of the sources S1 to S3 has a copy on the neglected side of the boundary. It was of interest to evaluate the pressure field arising from an excited pulse. Due to this, the *transient interface* and the pre-set study *time dependent* were chosen. The calculations in this interface are based on the classical wave equation, mentioned in 2.3.1. The model was evaluated with the boundary conditions; fully reflective, i.e. sound hard, walls.

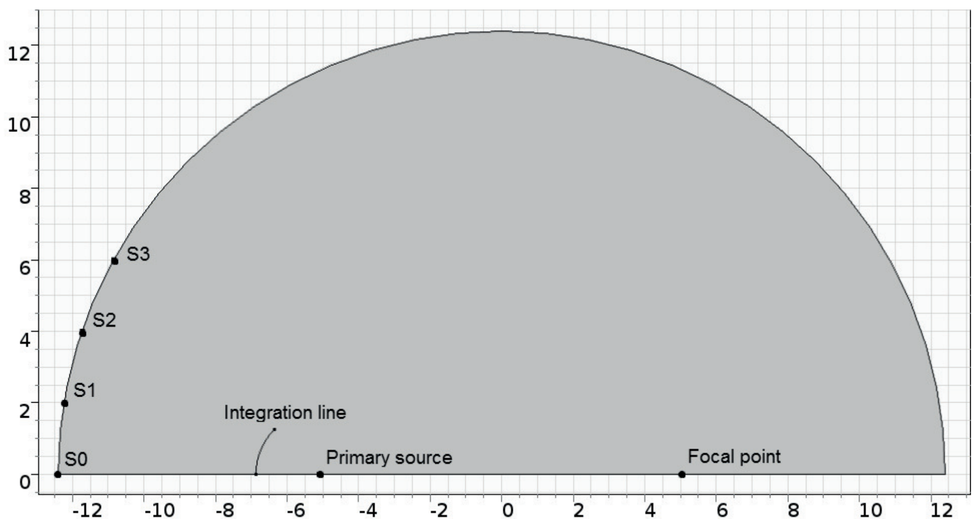


Figure 3.1: Comsol Set-up.

The primary source was chosen to be a Gaussian pulse (see Figure 2.5). It was placed at $x = -5.1$ metres from the origin (coordinates (-5.1, 0), roughly corresponding to the expected placement of a subwoofer). The pulse was chosen as it is the easiest way to evaluate sound in the time domain and the Gaussian configuration was chosen as it corresponds well with the shape of a real sound pulse and hence gives a distinct wave front. The pulse was given the time location 0.1 seconds and the standard deviation 0.004, as this implies a frequency content comprising 30 to 60 Hz (see Figure 3.2). The primary source was given the initial amplitude $gp2 \cdot (t \cdot 1[1/s])$ $[m^2/s]$, where gp2 denotes the Gaussian pulse constructed as in Equation 2.3 and the expression within the parenthesis assigns the unit, m^2/s, which is the volume flow in 2D. As all frequencies the mesh should resolve are contained in the excitation, no automatic time-step control is needed. The element size h_{max} was calculated with Equation 2.4 inserting $f_0 = 70$ Hz to be well adapted for the frequency range 30 to 60 Hz.

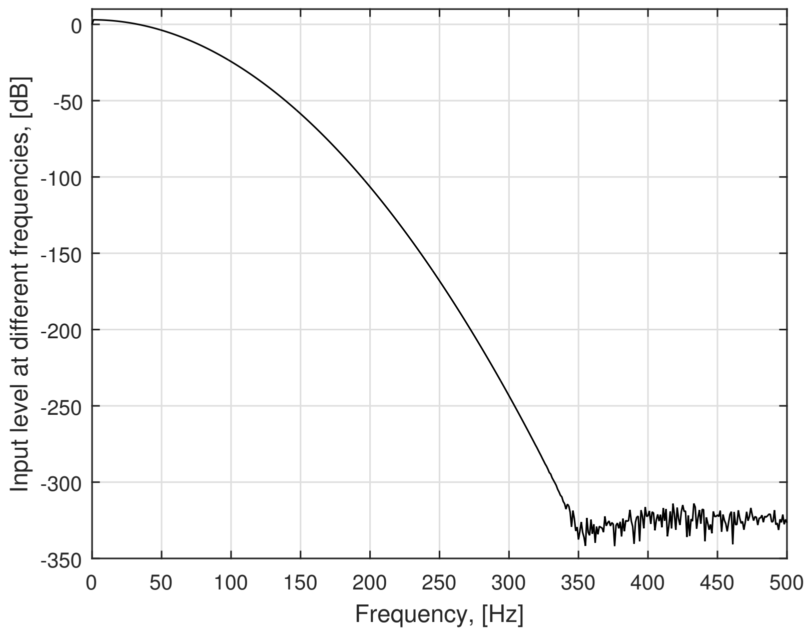


Figure 3.2: Frequency response of the implemented Gaussian pulse.

Furthermore, the recommended number of elements per wavelength, 5 to 10, mentioned in Section 2.3, was evaluated, due to accuracy and time consumption. It was found that 10 elements per wavelength gave an accurate result without consuming too much time and was therefore chosen for all calculations. Less than 10 elements per wavelength gave a less accurate result and more than 10 did not change the result from 10 elements per wavelength substantially.

The appropriate CFL number was evaluated by trial and error. It was found that the larger the CFL number gets the more diffuse focus of the pressure is obtained. The smaller CFL the more time consuming the calculation is. Due to this a number not too small and not too big, CFL = 0.05, was chosen.

The problematic area in the room was supposed to be a 90 degrees circular sector outwards from the source, being the most problematic close to the primary source. As the number of loudspeakers to be implemented in the scale model was limited to seven, only four secondary sources were implemented in Comsol due to the axis of symmetry. The axis of symmetry also limited the arc (wall) enclosing the problematic area to 6 metres due to the 45 degrees circular sector. The sources were equally spaced along this arc, i.e. 2 metres between each source, as this corresponded to a quarter of the wavelength of the centre frequency, 42 Hz, of the studied frequency band (according to what was stated in Section 2.2). The integration line in the room was placed at a quarter of the distance from the primary source to the four secondary sources, as this was supposed to be outside the near field and hence should be the area where the maximal control should be obtained (due to what was stated in Section 2.2). An additional receiver was placed in the focal point, as successful solutions of the problem theoretically should lower the pressure in this problematic position too (see Figure 3.1).

An initial study was done with only the primary source running. In this study the maximum pressure at the secondary source positions along the wall and in the primary source position were noted. The time of appearance of the highest pressure in the secondary source positions were used to appoint the temporal input of the secondary sources, which were constructed in the same way, with the same standard deviation, as the primary source (generating gp). The relation between the pressure in the secondary source positions and the primary source position was used to construct the input amplitude of the secondary sources. The relation between the two pressures was divided by minus two (negative amplitude due to opposite phase) to let the output from the secondary sources be governed by the control law: to only reduce the reflected sound wave and not the direct (see Equation 3.1 and Section 2).

$$A = gp(t \cdot 1[1/s]) \cdot \frac{p}{p_{primary} \cdot (-2)} \tag{3.1}$$

where gp denotes each constructed secondary source in the global settings, p the maximum pressure in each secondary source position and $p_{primary}$= 1966 Pa is the highest pressure the primary source obtains.

In the initial study the pressure on the integration line and in the focal point was also noted. These values were later compared to the studies of the implementation of ANC.

Ten different secondary source configurations were studied. The studies were evaluating the possibility to cancel out the first reflection from the primary source. The pressure reduction was examined in the same positions as in the study with only the primary source, i.e. integration line and focal point.

The first ANC configuration was to place only one secondary source in the position were the sound from the primary source first hits the wall (See S0 in Figure 3.1). In the second to fourth configurations the secondary sources S1-S3 where evaluated separately in the same way as the first configuration with only S0 working. These configurations contained two sources each, as the source on the neglected side of the axis of symmetry is included.

The fifth to ten configurations were evaluating whether the pressure reduction in the receiver positions could be further reduced using several secondary sources. In the fifth and sixth studies S0 and S1 respective S3 where running simultaneously. In the seventh study S0 was instead given twice the original amplitude. In the eighth configuration all secondary sources were implemented with their respective original amplitude. The ninth configuration was with S0 and S3 with their amplitude doubled. In the tenth study S0 was implemented with four times the original amplitude.

A short evaluation of how additional sources in-between the sources S0 to S3 would affect the result was done. This did not add any more advantage to the system and was therefore not further investigated.

The concluding remarks from the FE studies were used as indicator for the scale model measurements. The ANC configurations were evaluated in the measurements to see if they gave similar results as in FEM.

3.2 Scale model

Considering what was stated in 2.4, a 1:15 wooden scale model of the gas holder in Gävle was constructed. In this scale the dimensions were: height 71 centimetres and diameter 1.65 metres (see picture in Appendix A). The model was placed on a concrete floor and the ceiling was covered with a 10 centimetre thick absorber (Ecophon Industry Modus). A set of loudspeakers, Bose FreeSpace 3, were available for the tests. These loudspeakers had the dimensions 10x7x7 cm^3, which in the original scale corresponds to ordinary dual subwoofer systems. The loudspeaker had a good response in the studied frequency range and hence decided to be used (see directionality of the loudspeakers in Figure 3.3).

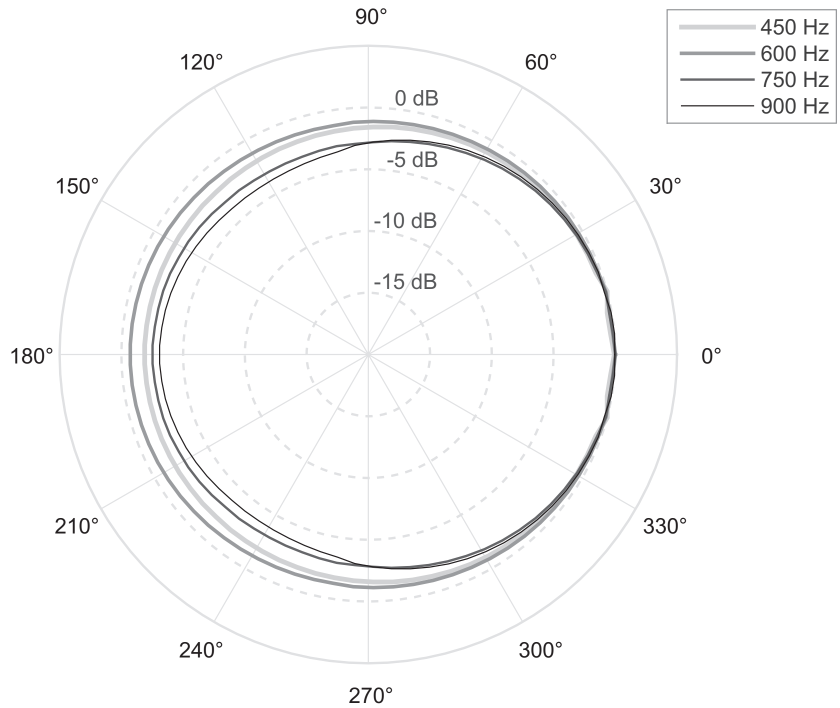


Figure 3.3: Directionality of the implemented loudspeakers.

The first tests in the scale model, aimed to investigate its acoustic properties (List of equipment and software in Table 3.1). The reverberation time, RT, and the impulse response were evaluated. The reverberation time was calculated using a loudspeaker at about 20 centimetres from the origin and measurements from nine microphones placed randomly in the horizontal plane at the approximate height of 10 centimetres (primarily in accordance with SS-EN ISO 354 (2003)). The Schroeder frequencies was furthermore calculated due to what was stated in 2.1.3. The impulse response was measured right in front of a loudspeaker placed in the origin. This position was evaluated as this would give information about how the initial sound pressure and the focal point sound pressure level are related to each other. The impulse response was additionally measured without ceiling. This was done to confirm the working range of the absorber, aiming for full absorption in the scaled frequency range 450 to 900 Hz.

Now, the primary loudspeaker was placed at the same distance from the origin as in the Comsol model, i.e. scaled distance of 34 centimetres, and was fed with band-passed white noise (250 to 1500 Hz). The sound pressure reduction from the direct sound to the first reflection was evaluated in the focal point and in the problematic position between the primary and secondary sources, i.e. 12 centimetres in front of the loudspeaker on the axis to the loudspeaker S0 (see Appendix B). This evaluation was done to later be able to investigate what sound pressure reduction the secondary sources could induce.

Seven secondary loudspeakers, the same type as the primary source, were placed in positions corresponding to the four secondary sources (and mirrored) in Comsol, i.e. with a centre distance of 14 centimetres (one fourth of a wave length of the centre frequency 630 Hz) (see picture in Appendix B). The loudspeakers were placed facing the wall to make the membrane of the loudspeaker get as close as possible to the wall. As this caused an offset of the secondary sources from the wall and the fact that there were losses in the wall, the control law was determined to not be identical to the one in Comsol, which was based on the assumption that half the identified pressure at the boundary had to be reduced. The control law was instead chosen to minimise the energy at the time of the arrival of the first reflection to the microphone placed 12 centimetres from the primary source. The main parameters governing the control law were the gain and delay of the signal from the secondary loudspeakers. These parameters would compensate for the offset and reflection coefficient of the wall, which contains information about the amount of sound pressure that is transmitted through the wall. To make it easier to adjust the gain and delay of the secondary source signals, e.g. use the same gain and delay for all studied frequencies, the impulse response of the primary source and secondary sources to the receiver microphone at 12 centimetres from the primary loudspeaker had to be determined. The impulse responses were cut to just compensate for the direct sound from each loudspeaker (for the secondary loudspeakers including the very first reflection from the closest wall). The cut impulse responses were then used to calculate the approximate inverse filter that should be fed to each loudspeaker in the ANC configurations (impulse response from the primary source to compensate for the loudspeaker itself). The inverse filters, which were calculated in Matlab, were 30th ($\pm$10) order IIR filters. The inverse filters were inserted in the Biquad boxes in the Simulink model shown in Figure 3.4, which was fed to a digital signal processor, *DSP*. As visualized in the Simulink model the time parameter delay and gain where given separate modification boxes for each secondary loudspeaker.

As a start, the delay and gain boxes were used to tune in the delay need to be in phase with the sound from the primary source and the negative gain giving a similar reduction as achieved in Comsol, i.e. 2.5-3 dB, for each loudspeaker couple (S0 unaccompanied). After finding the most preferable settings for each loudspeaker all loudspeakers where implemented simultaneously and the global gain for all secondary loudspeakers was modified aiming for the best reduction in the two critical areas/positions under study.

Furthermore, all ANC configurations implemented in Comsol were also evaluated in the scale model feeding the secondary sources with the same band-passed noise as to the primary loudspeaker using the real-time analyser Tamara 0.218. The achievement of the different configurations was evaluated in the same positions as before the ANC system was implemented. Additionally, the enhancement of the equivalent sound pressure level over third octave bands in the studied frequency range $L_{EQ,450-900}$ of each study was investigated in the two receiver positions. This could be determinant, as an increase of the equivalent sound pressure level would state the ANC configuration dysfunctional.

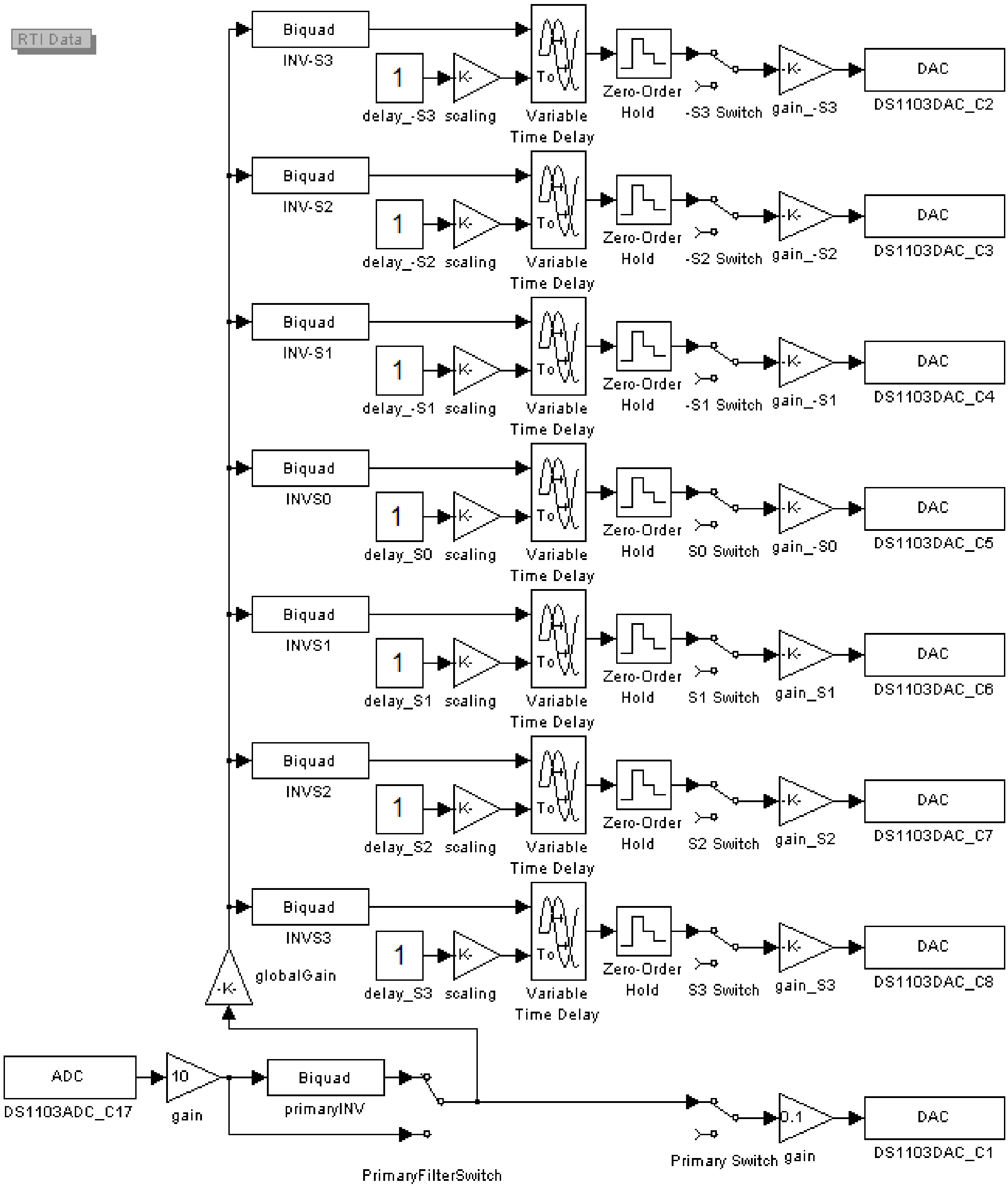


Figure 3.4: Simulink set-up. Each path belonging to one loudspeaker. The Biquad box contains the inverse filter measured for each of the loudspeakers. Each secondary loudspeaker path having separate delay and gain boxes, which are adjusted to give the most favourable impact on the sound field.

Another seven ANC configurations were implemented to investigate if the indications from the first ten configurations could be established for any combinations of secondary sources.

One of the configurations showing the most favourable results was further examined. The equivalent sound pressure level of discrete frequencies in the studied frequency band with and without ANC was studied. A sound file, Take My Breath Away by Boratto (2009), containing a sufficiently large amount of energy in the frequency band 30 to 60 Hz, was played with and without ANC to investigate whether there was any audible difference. The sound file was up sampled 16 times, to roughly correspond to the scale of the model, before played. The recording was then down sampled 16 times to match its original frequency range. The reverberation time RT was additionally evaluated.

Table 3.1: List of equipment and software.

	Manifacturer:	Model:	Sr. no.:
Analog filters	Chalmers Uni.	Fi16	
	Chalmers Uni.	Fi16	
DSP	dSpace	RT1103	
Power amplifier	Rotel	RMB-1048	976-5481100
Loudspeakers	Bose	FreeSpace 3 (x8)	
Microphones	Larson Davis	2520	1112
	Brüel & Kjær	4135	890688
	Chalmers Uni.	1/2" Electret (x8)	
Preamplifiers	Brüel & Kjær	2633	799474
	Brüel & Kjær	2639	1631107
Microphone power supply	Brüel & Kjær	2804	285276
	Chalmers Uni.	Pr26	
	Chalmers Uni.	Pr27	
Acquisition module	National Instruments	9234	177CF80
Acquisition chassis	National Instruments	9191	18DE657
Software	Multiphysics	Comsol	5.0
	dSpace	ControlDesk	3.4
	Chalmers Uni.	TriggerHappy	4.0
	Chalmers Uni.	Tamara	0.218
	MathWorks	Simulink	R2009a
	MathWorks	Matlab	R2015a

4 Results

In this chapter the results from the FE calculations and the measurements in the scale model are presented. Additionally, the results are commented on and some concluded remarks are listed.

4.1 FEM

The first study in Comsol was to investigate the propagation of the sound from the primary source. The sound propagation at different times is shown in Figure 4.1.

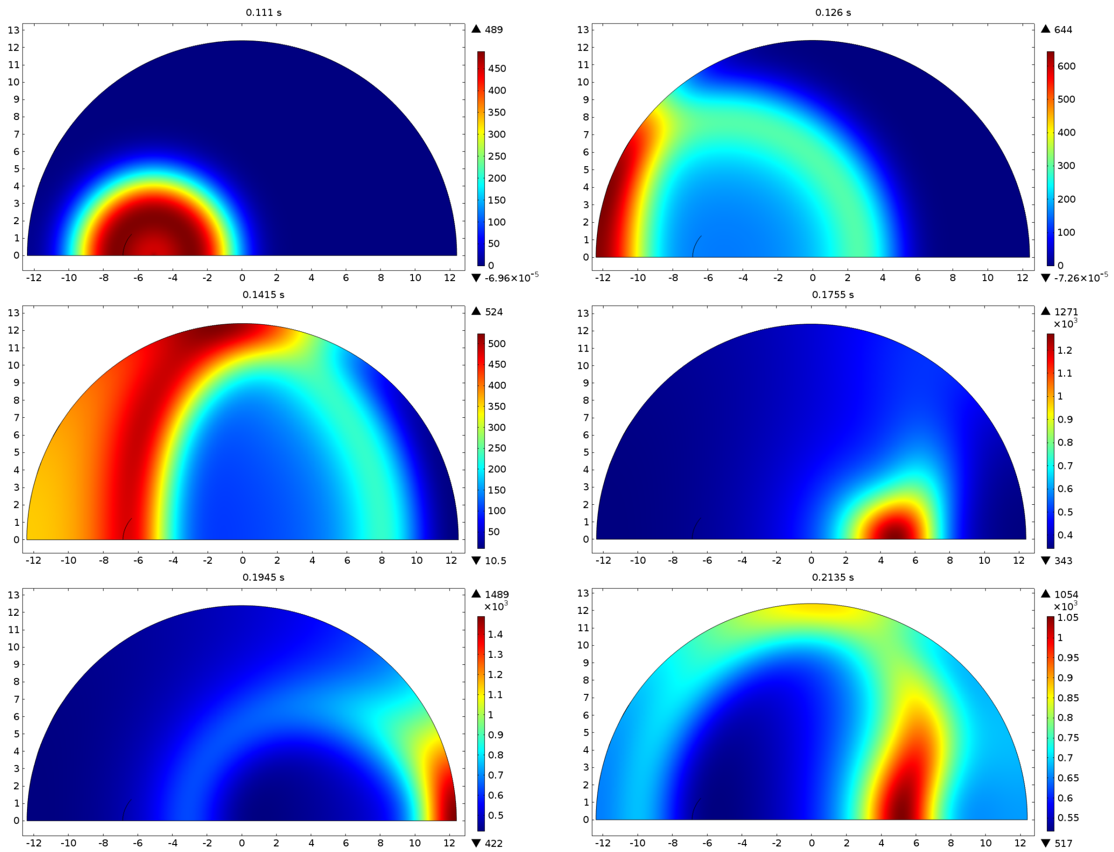


Figure 4.1: Sound propagation of the primary source. Colour legend in Pa.

In this study, it was examined at what time the first reflection from the primary source, which was excited at the time 0.1 seconds, arrives at the four secondary source positions. This time was used as temporal location in put for each of the secondary sources. The corresponding pressure in each secondary source position at the time of arrival was used to assign the input amplitude of each secondary source (see Equation 3.1). The maximum pressures and times of arrival are shown in Table 4.1.

Table 4.1: Time of wave arrival and pressure level at the secondary source positions. Used to construct the secondary sources.

Source	S0	S1	S2	S3
Time of arrival [s]	0.1245	0.125	0.126	0.1275
Pressure [Pa]	656	652	642	625
Pressure level [dB re. 1 Pa]	56.32	56.28	56.14	55.92

This study was also compared with the obtained pressure levels in the coming secondary source configurations. Ten studies with different secondary source implementations where evaluated, below referred to as ANC studies. The sound pressure on the integration line and in the focal point where evaluated in each study. In the initial study, with only the primary source running, it was found that the maximum pressure on the integration line after the first reflection occurs at 0.1415 seconds. It was also found that the maximum pressure in the focal point occurs at 0.1755 seconds. These times where the times when the pressure level of the ANC studies showed the initial deviation from the study with only the primary source running (see Figure 4.2).

The ten ANC studies gave different results. The first four ANC studies (S0, S1, S2 and S3 in Figure 4.2) with one mirrored secondary source barely showed any reduction. At the most they showed 3 dB reduction short after the time where the first reflection arrived at the integration line. At the time when the first focal point arose the pressure reduction only reached 1 dB. Short after the second focal point appeared, the same reduction as on the integration line was identified, i.e. 3 dB.

In the fifth to seventh ANC studies the reduction over time showed the same behaviour as the four previous studies (see S0+S1, S0+S3 and S0*2 in Figure 4.2), but with even more reduction. On the integration line the pressure was at the most reduced by 6-7 dB short after the arrival of the first reflection. In the focal point the reduction was 3 dB short after the appearance of the first focal and 9 dB after the second focal.

In the eighth to tenth ANC studies (see S0-S3, S0*2+S3*2 and S0*4 in Figure 4.2) the reduction increased compared to the previous studies. On the integration line the reduction reached at least 25, 31 and 18 dB lasting for 9 ms, 6 ms, 11.5 ms respectively short after the arrival of the first reflection. At the time when the first focal point appeared the reduction reached 6-7 dB and in the second focal point 20, 28 and 11 dB lasting for 8.5 ms, 5.5 ms and 15.5 ms respectively.

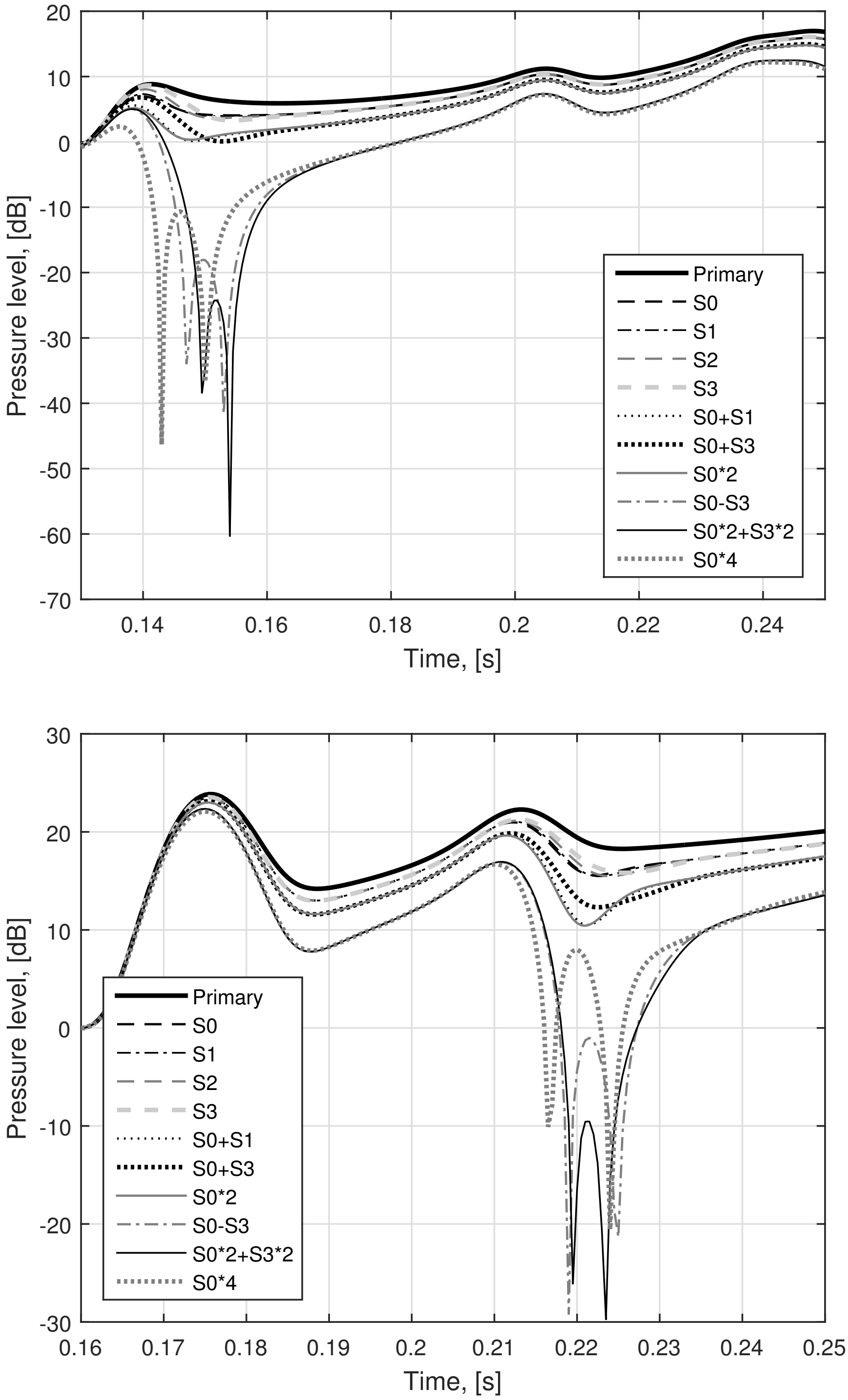


Figure 4.2: Calculations in Comsol. The upper plot showing the pressure level on the integration line and the lower the pressure level in the focal point. The plots are presented from the time where the results from the ANC studies deviate from the pressure levels when only the primary source is running.

4.1.1 Concluding remarks

The implementation of one pair of secondary sources (or in the case S0, one secondary source) needs a lot of power to be useful.

The investigations showed that the more total power that is fed from the secondary sources the more the reflection will be attenuated. From which secondary source the power is fed is not affecting the result significantly. The upper limit for the total power, where no longer a favourable result is obtained, was not investigated.

In all studies, the largest attenuation on the integration line appears at the time the first reflection arrives. In the focal point the largest attenuation appears at the time the second focal arises.

4.2 Scale model

The investigated properties of the scale model, reverberations time *RT* and the impulse response of a loudspeaker and microphone placed in the centre of the model, are presented in Figure 4.3. The average of *RT* over the frequencies 450 to 1500 Hz is 0.3471 seconds. It can be translated into the reverberation time of the original gas holder by a factor of 15, i.e. 5.207 seconds. The impulse response is presented with respect to distance. The sound pressure arising from the wall reflections occurs every 165 centimetres (the distance the sound has to travel from the loudspeaker to the walls and back to the loudspeaker). The shape of the impulse response when applying an absorber in the ceiling is in accordance with that of the scale model without ceiling. This implies that the dominant reflections in the scale model are the ones from the walls.

The Schroeder frequency of the room was calculated using Equation 2.2. The averaged *RT* mentioned above and the volume 1.5182 m^2 were inserted, giving the Schroeder frequency 956 Hz. This implies that the control should work in the studied frequency range 450 to 900 Hz.

An initial analysis of the behaviour of only the primary source was done. It was found that the arrival of the first reflection to the microphone 12 centimetres in front of the primary source, i.e. in the critical point, and the arrival of the first and second reflections to the focal point corresponded well with the travelling time found in Comsol and with the physical distance.

The same ANC configurations as in Comsol where implemented. Initially the studies S0 to S3 were tuned in (delay and gain) to reduce the sound pressure level by 2.8 dB in the critical point (see Table 4.2). This was done to approximately correspond to what the Comsol studies indicated. The settings barely affected the sound pressure level in the focal point. Both first and second focal had a deviation from the study with only the primary source running of ± 1 dB. The global gain was tuned in to give the largest reduction in the study where all secondary sources where implemen-

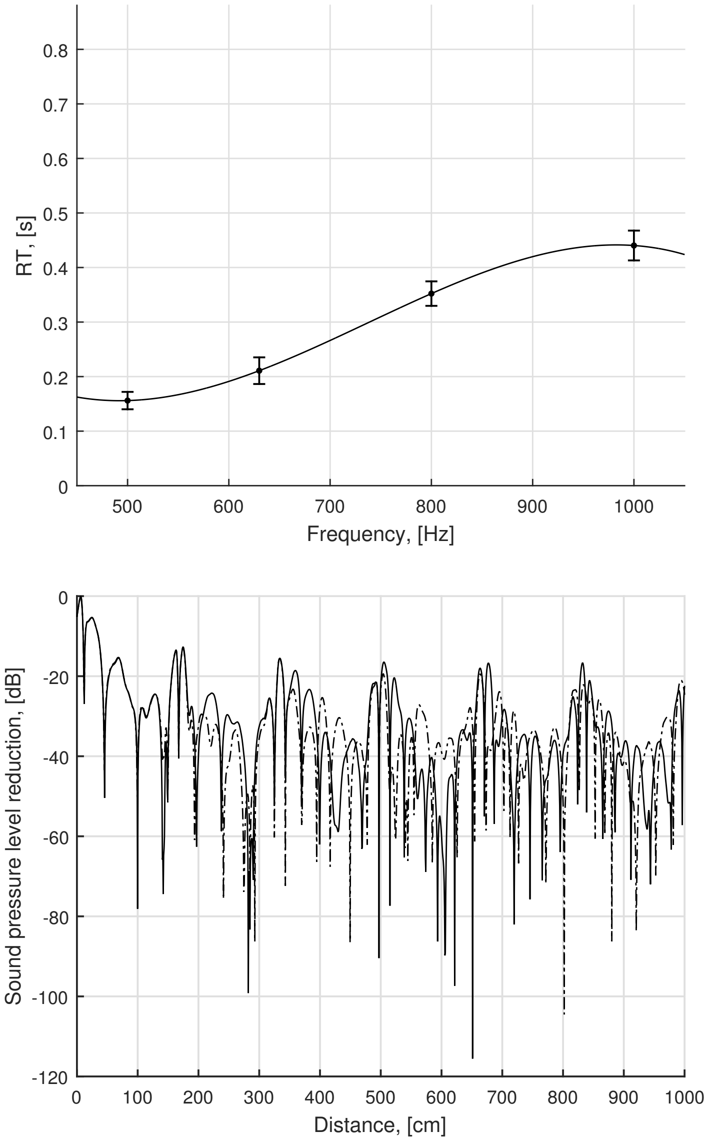


Figure 4.3: Reverberation time *RT* with standard deviation and impulse response of the scale model. Dash-dotted line is without ceiling. This is presented to demonstrate that the absorber in the ceiling makes the sound field mainly depend on the cylindrical wall.

ted, as this was what was obtained in Comsol. It was found that this was achieved when the global gain was 0.91. This caused a change in the reduction of sound pressure level for the studies S0 to S3 to 2.6 dB. The equivalent sound pressure level $L_{EQ,450-900}$ was measured in the critical point and focal point for each of the S0, S1, S2 and S3 configurations and compared with that of the study with only the primary source running. There was no obvious difference in the equivalent sound pressure level in these studies.

Table 4.2: Individual settings for each secondary source.

	Delay [samples]:	Relative gain:	Absolute gain:
S3	12	0.61	-0.00773
S2	9	0.34	-0.004371
S1	18	0.57	-0.007169
S0	17	1	-0.012685
-S1	18	0.57	-0.007169
-S2	14	0.34	-0.004371
-S3	18	0.61	-0.00773

The results from the further studies identical to the ones in Comsol, are presented in Table 4.3.

Table 4.3: Results from the scale model measurements similar to the studies performed in Comsol. Secondary sources S1 to S3 also include each source's respective negative counterpart from Table 4.2. Columns 1 to 3: Sound pressure level gain of the first reflection of the examined ANC configurations in the critical point *CP* and in the 1st and 2nd focal point *FP*. Columns 4 and 5: Equivalent sound pressure level gain of the frequency band 450 to 900 Hz in the studied position.

Study:	CP:	1st FP:	2nd FP:	$\Delta L_{EQ,450-900,CP}$:	$\Delta L_{EQ,450-900,FP}$:
S0+S1	-6 dB	-0.2 dB	-1.3 dB	0.4 dB	-1.1 dB
S0+S3	-6 dB	0.3 dB	-0.6 dB	0.5 dB	-0.3 dB
S0*2	-6 dB	-0.3 dB	-1.4 dB	0.5 dB	-0.8 dB
S0-S3	<-38 dB	0.4 dB	-1.4 dB	0.9 dB	-0.6 dB
S0*2+S3*2	<-38 dB	0.5 dB	-1.1 dB	1.4 dB	-0.2 dB
S0*4	<-38 dB	-0.6 dB	-3.1 dB	1.0 dB	-1.6 dB

When this was done some additional studies were performed to see if some small modifications could induce an even larger reduction. The results from these studies are presented in Table 4.4.

Table 4.4: Additional studies in the scale model. Values to compare with results in Table 4.3.

Study:	CP:	1st FP:	2nd FP:	$\Delta L_{EQ,450-900,CP}$:	$\Delta L_{EQ,450-900,FP}$:
S0+S2	-6 dB	0.1 dB	-0.7 dB	0.3 dB	-0.3 dB
S1+S3	-6 dB	0.4 dB	-0.4 dB	0.1 dB	0.1 dB
S1*2	-6 dB	-0.1 dB	-1.3 dB	0.3 dB	-0.8 dB
S2*2	-6 dB	0.5 dB	-0.1 dB	0.2 dB	0.2 dB
S3*2	-6 dB	0.8 dB	0.4 dB	0.9 dB	0.9 dB
S0*2+S1*2	<-38 dB	-0.5 dB	-3.0 dB	0.8 dB	-1.5 dB
S0*2+S2*2	<-38 dB	0.2 dB	-1.5 dB	0.7 dB	-0.7 dB

Further investigations were done with the S0*2+S1*2 configuration as it was one of the configurations showing the most improved values in Table 4.3 and 4.4. The equivalent sound pressure level over 1/24 octave bands in the studied frequency range (scaled to the original frequency band 30 to 60 Hz) with and without ANC was examined (see Figure 4.4). From these plots it was obvious that the focal point was affected more in the studied frequency range than the critical point. A sound file (Take My Breath Away (Boratto, 2009)) was also played with and without ANC and recorded in the critical point[1]. It was found that the low frequencies got more distinct and not as smeared out with ANC as without ANC in the critical point. The reverberation time *RT* was also measured for this ANC configuration. It was found to be insignificantly shorter than without ANC.

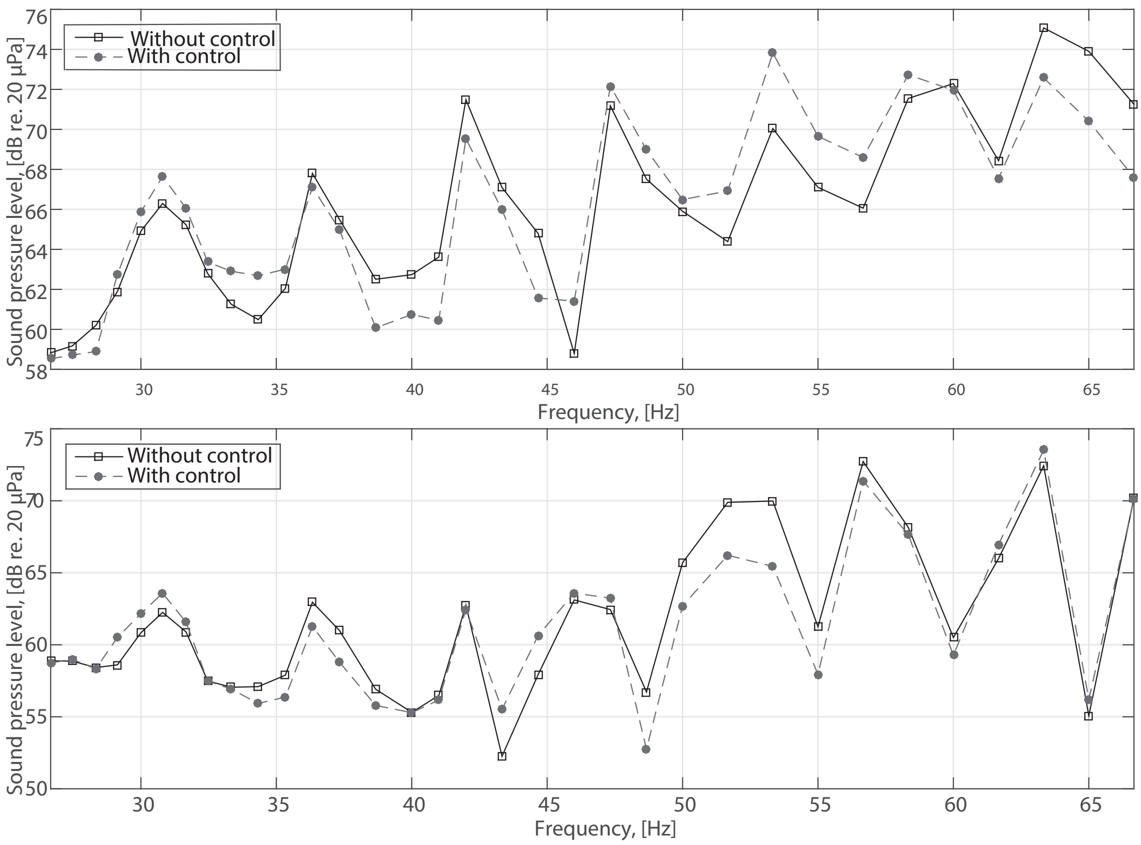


Figure 4.4: Equivalent sound pressure level over 1/24 octave bands in the studied frequency range (scaled). Upper plot showing the critical point and lower plot the focal point.

[1] It was not recorded in the focal point, due to miscalculations indicating that the critical point showed the largest reduction

4.2.1 Concluding remarks

Thirteen different ANC configurations where implemented in the scale model. Although, they showed different impacts on the sound field, some general effects were identified.

The assumption made from the FE calculations about the importance of the total power from the secondary loudspeaker was confirmed. To have one powerful loudspeaker can be as useful as having seven loudspeakers with a seventh of the power fed to each of them. This, together with the observation that the focal point was not substantially affected by the implementation of ANC in a 90 degrees circular sector, indicates that a small number of loudspeakers distributed equally along the whole circumference would show a larger reduction in the focal point.

The configurations S0-S3, S0*2+S1*2, S0*2+S2*2, S0*2+S3*2 and S0*4 showed the most favourable reduction of the first reflection to the critical point. They all showed the similar reduction (>38 dB) in the critical point, which was expected as they all contain the same total power.

In all other configurations (S0+S1, S0+S3, S0*2, S0+S2, S1+S3, S1*2, S2*2, S3*2) half the power, of the above mentioned, was fed to the loudspeakers. This only caused a 6 dB reduction in the critical point.

In all configurations there was no substantial reduction or increase of the pressure level of the first focal, second focal or the equivalent sound pressure level. The behaviour of the first focal was in accordance with the FE calculations. The ANC configurations did not affect the behaviour of the second focal in the scale model measurements significantly, which was in contradiction with the FE calculations.

Although there was no significant sound pressure reduction of the first reflection to be observed in the first and second focal point, it is obvious from the equivalent sound pressure in 4.4 that the focal point is reduced over time in the whole frequency range. The equivalent sound pressure in the critical point is not as distinct. The frequencies below 45 Hz obtain a lower sound pressure and a higher sound pressure at frequencies between 45 and 60 Hz when ANC is implemented.

The sound file that was played in the scale model showed that there was an audible difference in the critical point with the ANC system implemented, although the critical point had a smaller reduction of the equivalent sound pressure level than the focal point. This implies that the audible difference between with and without ANC may be even larger in the focal point.

5 Analysis of methods

Two different methods, FE calculations and scale model measurements, were used to evaluate whether an ANC system can be useful in a gas holder to suppress low frequencies.

The two methods were based on two different control law, due to differences in the physical conditions. The FE calculations were done for the perfect conditions that the wall was fully reflective and that the secondary sources were placed directly on the room boundary. The scale model did not have fully reflective wall and it was impossible to place the loudspeakers flush in the wall. The control law used in Comsol, to suppress half the pressure at the boundary, could therefore not be translated to the scale model, due to losses. This could be a reason to question the reliability of comparing the results from the two methods.

In the critical point, between the primary and secondary sources, similar results where obtain in both methods. In the focal point there was a large difference between the two methods. FEM showed a larger reduction when the ANC system was implemented than the scale model measurements did. At the time when the second reflection arrived to the focal point the reduction got very large in FEM but was close to absent in the scale model measurements. The difference in the obtained results from the two methods indicates that a discussion about possible changes in the method that may change the results is required.

5.1 FEM

In Comsol a Gaussian pulse was used to excite the pressure field. This was done as it turned out to be the most appropriate way to create a distinct wave front. A Dirac pulse is moreover theoretically more suitable when a transient is demanded. However, this can most likely be expected to have minor influence on the outcome.

The construction of the secondary sources was based on the assumed that the observed pressure at the walls is the direct sound and the reflected sound together (no losses). Due to this, half the pressure at the walls was intended to be suppressed by the ANC system. It can be questioned whether this assumption should be done or not.

The first focal was scarcely affected by the ANC implementation. This could be derived from that the focal point, contrary to the critical point, is more affected by the reflections from the parts of the wall that are not provided with secondary sources. To provide the part of the wall not having any secondary sources with non-reflective characteristics might have shown a more reliable influence from the ANC system on the first focal.

The large reduction of the second focal in the FE calculations implies that there could be a limitation in using Comsol. This is also based on the results from the scale model measurements, which did not show any substantial reduction at the time when the second focal appears.

5.2 Scale model measurements

The properties of the scale model did not fully correspond to the properties of the gas holder in Gävle. Due to this, the obtained results from the scale model measurements cannot be completely translated to the gas holder. The results work as indications of the possible improvements that could be obtained with a ANC system in cylindrical rooms.

The loudspeakers used in the scale model had a working range that was favourable for the studied frequency range. The dimensions of the loudspeaker boxes corresponded well with the dimensions of ordinary dual subwoofer systems. This made the possible influence on the results from the loudspeaker boxes agree with the expected full-scale results.

To be able to compare the two methods, it was decided to tune in the gain of the secondary sources to correspond to the obtained results from the configurations consisting of one pair of loudspeakers (S0 alone) in Comsol. This was done as the pre-set parameters in Comsol could not easily be translated. It can be questioned whether the scale model approach should have been performed independently from what was obtained in Comsol.

The sound pressure level in the focal point was barely affected for any of the ANC configurations. This was not astonishing, as the system was constructed to have the best suppression in the critical point. Moreover, like in the FE calculations, the reflections from the part of the wall that is not provided with secondary loudspeakers can be assumed to have a large effect on the pressure level in the focal point.

In the scale model measurement an off-line ANC system was implemented. This method is based on the fact that the fed signal to the loudspeakers is known, i.e. amplitude, phase and delay. An on-line system with microphone measurements updating the inverse filters to the secondary sources by means of an algorithm, e.g. LMS, may have offered a more flexible system, more efficient control and adaptability for acoustic performances.

The constructed ANC system, i.e. Simulink model and loudspeaker placement, turned out to suppress the energy from the first reflection in the critical point at frequencies between 450 and 900 Hz (30 to 60 Hz in the original scale). This was concluded for different input signals, e.g. noise and music, both visually in plots and audibly. As the suppression was fairly large, it can be assumed that the control law was chosen in a favourable manner. And furthermore, that the system can be translated to any room, given that the impulse responses inserted in the inverse filters are measured in the current room and that the delay and gain are again tuned in.

6 Conclusions

This thesis has proved that active noise control can be used to suppress unwanted noise at low frequencies in large cylindrical rooms, e.g. gas holders. It was found that a set of secondary sources along a crucial part of the boundary of the room can help to create a more free field-like environment by suppressing the first reflection from the wall.

Both finite element calculations and scale model measurements showed that the sound pressure level of the first reflection from the walls in a critical point between the primary and secondary sources was reduced when the secondary sources were implemented. The implementation did not have an as large effect on the sound pressure level of the first and second appearance of the focal point, but did instead show a larger equivalent sound pressure level reduction over the studied frequency range than it did in the critical point.

It was concluded that the governing parameter of the active noise system is the total power fed to the system. The number of secondary subwoofers at the hall boundary and their distribution are thus of minor importance.

6.1 Future work

In this project only a 2D FE model was examined. It could therefore be of interest to do some complementary studies in a 3D model to see how reflections in the vertical direction would influence the pressure field. This would also provide the possibility to investigate if placing secondary sources at different heights and on top of each other could induce an improvement of the ANC system. To investigate this in the scale model could consequently be of interest.

The ANC configurations were only studied in time domain in the FE calculations. It could be useful to instead do the investigations in the frequency domain, to be able to do separate simulations for discrete frequencies.

The secondary loudspeakers were placed facing the wall in the scale model. The goal was to place the loudspeaker membrane as close to the wall as possible. Due to the loudspeaker construction the membrane had to be placed with an offset from the wall. Therefore mounting of them flush in the wall could be interesting to investigate.

To construct an ANC system aiming to reduce the sound pressure level in the focal point could be of interest. This could include formulation of a control law, determination of a digital filter and to examine if it is possible to suppress the focal point and critical point with the same system.

Due to the placement of the secondary loudspeakers in the scale model, the control law had to be constructed differently to the one in FEM. A study on suitable control laws for both FEM and the scale model measurements could be something to do in the future. To investigate whether a different control law could be used to obtain similar or better results than what was obtained and to evaluate if the ANC system is beneficial in more positions than the two under study could be of interest. Furthermore, to see if the chosen system causes an even frequency response in a large area in the hall would be desirable.

Possible advantages with implementing an on-line system to optimise the digital filter governing the ANC system could be something to further investigate.

To further investigate the upper limit for the total power fed from an ANC system, where no longer a favourable result is obtain, could be further investigated.

References

Baukal, C. E. J. (2004). *Industrial Burners Handbook*. CRC Press, 1 edition. 0-8493-1386-4.

Beogubtsev, E. S. & Kuznetsov, G. N. et al. (2011). Physical Modeling of Active Cancellation of Low-Frequency Sound Signals. *Physics of Wave Phenomena*, Vol. 19(No. 3):210–223.

Birkedal, S. N. & Celestinos, A. (2007). Time based room correction system for low frequencies using multiple loudspeakers. *AES 32nd International Conference*, pages 30–39.

Boratto, G. (2009). *Take my breath away*; Take my breath away. Kompakt, compact disc, KOMCD70.

Comsol Multiphysics (2012). *Introduction to Acoustics Module*, 4.3 edition.

Comsol Multiphysics (2014). *Transient Gaussian Explosion*, 5.0 edition.

Corakci, A. C. & Tober, S. (2009). Modeling of interior sound field in railway vehicles. Master thesis, Division of Applied Acoustics, Chalmers University of Technology, Sweden.

Gävle Kommun (2014). Gasklockorna i Gävle. `http://www.gasklockornagavle.se/`, accessed February 11, 2015.

Hornikx, M. (2009). *Numerical modelling of sound propagation to closed urban courtyards*. PhD thesis, Chalmers University of Technology.

Kropp, W. (2014). Active Noise Control, Lecture 1. `http://www.ta.chalmers.se/downloads/students/cpg_anc/ANC_Fo1.pdf`, accessed June 4, 2015.

Lagö, T. (2008). Basic Principles. In *ANVC Cource for Industry*. Acticut International AB.

Lindegren, A. W. (2013). Kulturminnesmärk Värtagasverket och dess speciella bebyggelse. `http://www.stockholmskyline.se/2013/05/kulturminnesmark-vartagasverket-och-dess-speciella-bebyggelse/`, accessed February 11, 2015.

Linkwitz Lab (2015). Room Acoustics. `http://www.linkwitzlab.com/rooms.htm`, accessed June 4, 2015.

Long, M. (2006). *Architectural Acoustics*. Academic Press. 978-0-12-455551-8.

Marburg, S. & Nolte, B. (2008). *Computational Acoustics of Noise Propagation in Fluids - Finite and Boundary Element Methods*. Springer Verlag. 978-3-540-77447-1.

Möser, M. (2009). *Technische Akustik*. Springer Verlag, 8. edition. 978-3-540-89817-7.

Nelson, P. A. & Elliott, S. J. (1992). *Active Control of Sound*. Academic Press. 0-12-515425-9.

Nilsson, G. (2002). Miljöteknisk undersökning Klaraborgs gasverk, Karlstad. http://www.lansstyrelsen.se/varmland/SiteCollectionDocuments/Sv/miljo-och-klimat/verksamheter-med-miljopaverkan/fororenad-mark/klaraborg.pdf, accessed February 23, 2015.

Ottosen, N. & Petersson, H. (1992). *Introduction to the Finite Element Method*. Prentice Hall. 0-13-473877-2.

Oxford University Press (2015). Oxford Dictionaries. http://www.oxforddictionaries.com/, accessed May 12, 2015.

Russell, T. (2014). The Maufactured Gas Industry in Europe. file:///C:/Users/verjon/Downloads/Gasworks%20in%20Europe.pdf, accessed February 23, 2015.

SS-EN ISO 354 (2003). Acoustics-Measurement of sound absorption in a reverberation room.

Welti, T. (n.d.). Subwoofers: Optimum numbers and locations. http://www.harman.com/EN-US/OurCompany/Innovation/Documents/White%20Papers/multsubs.pdf, accessed February 23, 2015.

Yue, B. & Guddati, M. N. (2005). Dispersion-reducing finite elements for transient acoustics. *Journal of the Acoustical Society of America*, Vol. 118(No. 4):2132–2141.

A Scale model

Figure showing the 1:15 wooden scale model.

B Loudspeaker placement

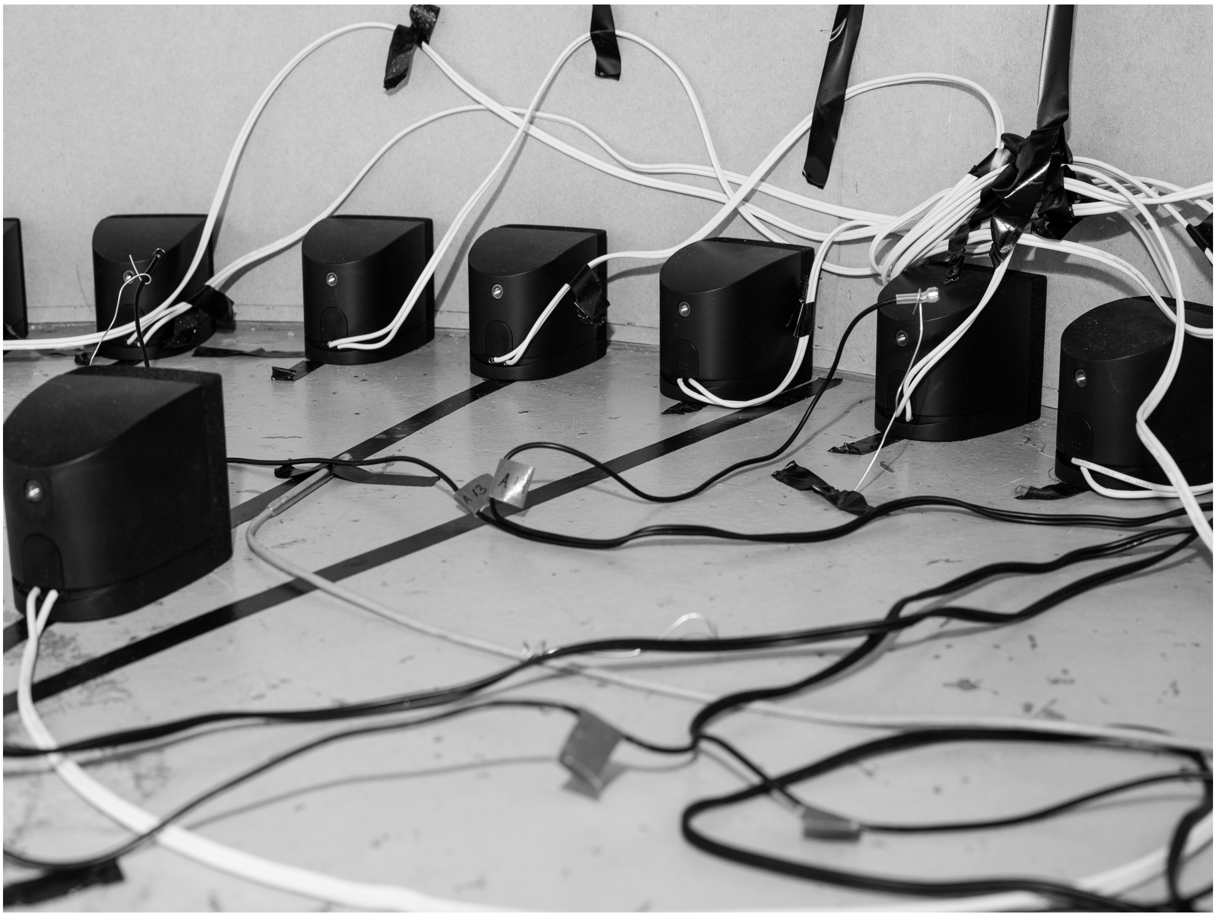


Figure showing one primary source, seven secondary sources and the receiver microphone 12 centimetres in from of the primary source on the axis between the primary source and the centre secondary source.