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Free-field Reciprocity Calibration of Condenser Microphones in the Low Ultrasonic Frequency Range

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Nourreddine BOUAOUA

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Erstgutachter: Prof. Dr. Volker Mellert

Zweitgutachter:
PD. Dr. Achim. Kittel
Dr. Thomas Fedtke

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CONTENTS

SUMMARY

Free-field reciprocity calibration of condenser microphones in the low ultrasonic frequency range

Recent years have seen an increased use of ultrasound in medical and industrial applications, such as medical therapy and diagnosis, material characterization, cleaning, welding of metal and plastic, measuring distance in buildings, as well as in consumer devices such as camera rangefinders, automatic door openers, parametric ultrasound loudspeakers, etc. Therefore, there is a significant risk of exposure to high-level airborne ultrasound, which may be harmful for the hearing or have negative bio-effects on man. To ensure the safety of persons against this exposure, ultrasound levels in air must be measured with calibrated devices traceable to the national standard.

The standard of sound pressure is defined by means of the sensitivities of 1-inch (LS1P) and ½-inch (LS2P) condenser microphones, calibrated with the reciprocity method. But these two microphone types have a limited frequency range (maximum frequency 40 kHz for ½-inch microphones and 20 kHz for 1-inch microphones). Thus, for the reasons cited above, a primary standard in the low ultrasonic frequency range needs to be established.

This thesis describes the development of a measurement set-up for the free-field calibration of ¼-inch condenser microphones by the reciprocity method, and enables traceable measurements of the free-field sensitivity of condenser microphones in the low ultrasonic frequency range from 20 kHz to 160 kHz. A new, fully automated measurement set-up for free-field reciprocity calibration of ¼-inch condenser microphones has been established, and a procedure for the calculation of the free-field sensitivity of ¼-inch condenser microphones is described.

A new preamplifier having the diameter of ¼-inch condenser microphones was designed and manufactured to allow the measurement of the open-circuit voltage of ¼-inch condenser microphones when used as receiver microphones. The free-field performance of the anechoic room was then tested in the ultrasonic frequency range from 20 kHz to 160 kHz, by analyzing the deviation of the measured sound pressure of the receiver microphone as function of distance between the transmitter and receiver microphones from the inverse distance low. The results of this test showed a good free-field performance of the anechoic room and the deviation from the ideal free-field behavior over this frequency range was due to the interaction between the transmitter and receiver microphones (crosstalk and standing waves).

The parameters influencing the measurements (acoustic and electric noise, crosstalk, distortion, measurement distance, standing waves and reflections, environmental conditions) were studied and optimised. The acoustic centers of the condenser microphones have been determined by measuring the sound pressure as a function of distance and by using the property of spherical waves, that the sound pressure is inversely proportional to the distance from the source. The static pressure coefficients of ¼-inch condenser microphones have been measured as a function of frequency by using an electrostatic actuator.

Measurement results for the free-field sensitivity of ¼-inch condenser microphones are given in the ultrasonic frequency range from 20 kHz to 160 kHz in 1/3-Octave steps. The components of the measurement uncertainty were calculated following the GUM rules with a model based on the free-field sensitivity formula. By also measuring their electrostatic actuator response, free-field correction values characterizing this type of microphones have been deduced from the difference between the free-field sensitivity and the sensitivity determined by means of the electrostatic actuator.

One of the problems in implementing the set-up of the free-field reciprocity calibration of condenser microphones is the realization of the free-field conditions, which could be affected by non-ideal performance of the anechoic room resulting on minute reflections from the walls. Free field can be also affected by the interaction between the microphones coupled in free-field resulting on standing wave and crosstalk. These disturbances can have a significant influence on the measured free-field sensitivity. These effects can be eliminated in the time domain by means of a time selective window applied to the impulse response.
The end of this thesis describes the use of a time selective technique permitting the identification of undesirable disturbances due to crosstalk, standing waves and reflections and the possibility of their elimination.

ZUSAMMENFASSUNG

In den letzten Jahren wurde ein zunehmender Einsatz von Ultraschall in medizinischen und industriellen Anwendungsbereichen beobachtet, wie zum Beispiel bei Therapie und Diagnose in der Medizin, Materialcharakterisierung, Reinigung, Schweißen von Metall und Plastik, Längenmessungen in Gebäuden und bei Verbrauchergeräten, wie z.B. Sucherkameras, automatischen Türöffnern, parametrischen Ultraschalllautsprechern usw. Es besteht daher ein beachtliches Risiko einer Belastung durch hohen Luftschall, der dem Gehör schaden oder negative biologische Auswirkungen auf den Menschen haben kann. Um die Sicherheit von Personen gegen diese Belastung zu gewährleisten, müssen Luftschallpegel mit kalibrierten Geräten gemessen werden, die auf das nationale Normal rückführbar sind.

Das Schalldrucknormal wird durch die Übertragungsfunktionen von 1-Zoll (LS1P)- und ½-Zoll (LS2P)-Kondensatormikrophonen definiert, die nach dem Reziprozitätsverfahren kalibriert wurden. Diese beiden Mikrophonarten haben jedoch einen begrenzten Frequenzbereich (Obere Grenzfrequenz: 40 kHz bei ½-Zoll-Mikrophonen und 20 kHz bei 1-Zoll-Mikrophonen). Daher ist es aus den oben genannten Gründen erforderlich, ein Primärnormal im unteren Ultraschall-Frequenzbereich festzulegen.
Diese Dissertation beschreibt die Entwicklung eines Messplatzes für die Freifeld-Kalibrierung von ¼-Zoll-Kondensatormikrophonen nach dem Reziprozitätsverfahren, das rückführbare Messungen der Freifeld-Übertragungsfunktion von Kondensatormikrophonen im unteren Ultraschallfrequenzbereich von 20 kHz bis 160 kHz ermöglicht. Es wurde ein neuer, vollautomatischer Messplatz für die Freifeld-Reziprozitätskalibrierung von ¼-Zoll-Kondensatormikrophonen errichtet, und es wird ein Verfahren zur Berechnung der Freifeld-Übertragungsmaßes von ¼-Zoll-Kondensatormikrophonen beschrieben.

Ein neuer Vorverstärker, der den Durchmesser von ¼-Zoll-Kondensatormikrophonen hat, wurde entworfen und hergestellt, um die Leerlaufspannung von ¼-Zoll- Kondensatormikrophonen zu messen, wenn diese als Empfängermikrophone verwendet werden. Dann wurden die Freifeldeigenschaften des reflexionsarmen Raums im Ultraschallfrequenzbereich von 20 kHz bis 160 kHz geprüft, indem die Abweichung des gemessenen Schalldrucks des Empfängermikrophons in Abhängigkeit vom Abstand zwischen den Sender- und Empfängermikrophonen mit Bezug auf das Abstandsgesetz analysiert wurde. Die Ergebnisse dieser Prüfung zeigten gute Freifeldeigenschaften des reflexionsarmen Raums, und die Abweichung vom idealen Freifeldverhalten über diesen Frequenzbereich war auf die Interaktion

zwischen Sender- und Empfängermikrophonen zurückzuführen (Übersprechen und stehende Wellen).
Die Parameter, die die Messungen beeinflussen (akustisches und elektrisches Rauschen, Übersprechen, Verzerrung, Messabstand, stehende Wellen und Reflexionen, Umgebungsbedingungen) wurden untersucht und optimiert. Die akustischen Zentren der Kondensatormikrophone wurden durch Messung des Schalldrucks in Abhängigkeit vom Abstand sowie durch Verwendung der Eigenschaft von Kugelwellen, dass der der Schalldruck umgekehrt proportional zum Abstand zur Quelle ist, bestimmt. Die statischen Druckkoeffizienten von ¼-Zoll- Kondensatormikrophonen wurden in Abhängigkeit von der Frequenz und unter Verwendung einer elektrostatischen Anregeelektrode gemessen.

Im Ultraschallfrequenzbereich von 20 kHz bis 160 kHz werden die Messergebnisse für das Freifeld-Übertragungsmaß von ¼-Zoll-Kondensatormikrophonen in Terzschritten angegeben. Die Komponenten der Messunsicherheit wurden in Anlehnung an die GUM-Regeln mit Hilfe eines auf der Berechnungsformel für das Freifeld-Übertragungsmaß beruhenden Modells berechnet. Durch gleichzeitige Messung des Frequenzganges mittels einer elektrostatischen Anregeelektrode wurden Freifeld-Korrekturwerte aus der Differenz zwischen Freifeld-Übertragungsmaß und Anregeelektroden-Übertragungsmaß abgeleitet.

Eines der Probleme bei der Errichtung des Messplatzes für die Freifeld-Reziprozitätskalibrierung von Kondensatormikrophonen war die Realisierung der Freifeldbedingungen, die durch nicht-ideale Freifeldeigenschaften des reflexionsarmen Raums, welche zu kleinen Reflexionen von den Wänden führen könnten, beeinflusst werden können. Das freie Feld kann auch durch die Interaktion zwischen den im Freifeld gekoppelten Mikrophonen beeinflusst werden, was zu stehenden Wellen und Übersprechen führt. Diese Störungen können einen bedeutenden Einfluss auf die gemessene Freifeld-Übertragungsfunktion haben. Diese Effekte können im Zeitbereich durch ein zeitselektives Fenster, das auf die Impulsantwort angewendet wird, behoben werden. Am Ende dieser Doktorarbeit wird eine zeitselektive Technik beschrieben, durch die unerwünschte Reflexionen aufgrund von Übersprechen, stehenden Wellen und Reflexionen beseitigt werden können.

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CHAPTER I

GENERAL INTRODUCTION

CHAPTER I. GENERAL INTRODUCTION

The standard of sound pressure is defined by means of the sensitivities of 1-inch (LS1P) and ½-inch (LS2P) condenser microphones, calibrated with the reciprocity method. But these two microphone types have a limited frequency range (maximum frequency 40 kHz for ½-inch microphones and 20 kHz for 1-inch microphones). However, the applications using airborne ultrasound in medical and industrial applications have recently been increasing. Therefore, there is a need to extend the frequency range of the standard of sound pressure towards higher frequencies. The work described in this thesis deals with the realization of a standard of sound pressure in the ultrasonic frequency range for free-field conditions.

This chapter is a general introduction to the thesis; its first part includes a brief introduction to metrology and measurement standards. The second part discusses sound pressure standards. The next paragraph describes different methods permitting the calibration of microphones. A brief description of the free-field reciprocity calibration of microphones until today is discussed in the fourth part. The motivation of the project is then detailed, including examples of airborne ultrasound sources, the effects of airborne ultrasound, and finally, the current actual recommendations for airborne ultrasound exposure limits are described. The sixth part discusses the need for a primary standard at higher frequencies. This chapter ends with a short description of the thesis' contents, including the contributions of the following chapters.

I.1 Metrology and measurement standards

Metrology is the science of measurement, comprising both experimental and theoretical aspects in any field of science and technology. Measurement is a fundamental procedure for gaining knowledge and in controlling systems. It is the process of attributing numbers to the properties of objects and events in order to describe them.

In Germany, the Physikalisch-Technische Bundesanstalt (PTB) performs fundamental research and development in the field of metrology. PTB has the responsibility determining fundamental constants, realizing and disseminating the units called primary standards with the highest precision. Each field of physical measurements has its own primary standard. In acoustics, which has several branches, e.g. audiology, building acoustics, ultrasounds, noise measurement, and others, all measurements are based on sound pressure; the primary standard is therefore derived from this quantity.

I.2 Sound pressure standards

The standard of sound pressure in air is realized indirectly by means of the sensitivity of condenser microphones, calibrated with the reciprocity method. The use of condenser microphones for measuring sound pressure will change its value because of the interaction between the sound wave and the measuring microphone, called diffraction. Therefore, a microphone is characterized by different sensitivities when placed in different sound fields; there are three different sensitivities:

Pressure sensitivity, when measurements are done in enclosures or cavities, which are small, compared to the wavelength. It is defined as follows [IEC2000]:
For a sinusoidal signal of a given frequency and for given environmental conditions, the quotient of the open-circuit output voltage of the microphone by the sound pressure acting over the exposed surface of the diaphragm, the sound pressure being applied uniformly over the surface of the diaphragm.

Free-field sensitivity, when measurements are realized in an anechoic room where sound waves can propagate freely without any disturbing objects. It is defined as follows [IEC2000]:
For a sinusoidal signal of a given frequency, for a specified direction of sound incidence and for given environmental conditions, the quotient of the open-circuit output voltage of the microphone by the sound pressure that would exist at the position of the acoustic center of the microphone in its absence.

Diffuse-field sensitivity, when measurements are made in a reverberation room. It is defined as follows [IEC2000]:
For a sinusoidal signal of a given frequency in a diffuse field and for given environmental conditions, the quotient of the open-circuit output voltage of the microphone by the sound pressure that would exist at the position of the acoustic center of the microphone in its absence.

The unit of these sensitivities is V/Pa, and is usually expressed as ‘’sensitivity level’’ in decibels (dB) with a reference value of 1V/Pa.

I.3 Calibration of condenser microphones

The calibration of condenser microphones can be divided into two categories: primary and secondary methods. Each method has its advantages and disadvantages depending on the frequency range, the amplitude and measurement uncertainty.
Secondary methods include the pistonphone method, the electrostatic actuator method, and the comparison method.

Comparison calibration

For comparison calibration methods, the condenser microphone to be calibrated is compared to a reference microphone of a known sensitivity, calibrated by a primary method.

Pistonphone calibration

In pistonphone calibration, a mechanically driven piston produces a known time-varying volume displacement in a small cavity of known volume. Because of practical mechanical problems, the pistonphone is used only at low frequencies, for example 250 Hz**.**

Electrostatic actuator calibration

The electrostatic actuator calibration set-up consists of a metallic grid positioned close to the diaphragm of the condenser microphone. An alternating voltage superimposed by a direct voltage is applied between the metallic grid and the microphone diaphragm, and from the resulting electrostatic force, the equivalent sound pressure is calculated. This method presents a poor accuracy because the force depends on the distance between the actuator and the microphone diaphragm, which is difficult to measure with high accuracy. The sensitivity of the condenser microphone at a reference frequency is measured by a pistonphone, and the actuator is used for the determination of the frequency response relative to this frequency.

Reciprocity calibration

The reciprocity calibration is a primary method based on the reciprocity of reversible condenser microphones. It is carried out by permuting three condenser microphones and measuring the electrical transfer impedance, with the knowledge of the density and the attenuation of air. Reciprocity calibration can be carried out in a free field, pressure field or diffuse field. This method enables an absolute calibration of condenser microphones with high accuracy and can be applied at many frequencies. However, it is a time-consuming and expensive operation. Microphones calibrated with the reciprocity method can be used as acoustical reference standards.

I.4 Development of free-field reciprocity calibration

Free-field calibration of condenser microphones was first realized by using Rayleigh disk. MacLean [MacLean1940] and Wathen-Dunn [Wathen-Dunn1947] developed the theory of the free-field reciprocity calibration of microphones. Rudnick and Stein [Rudnick1948] developed the experimental implementation of this technique. Later, Terry [Terry1951] and Niemoler [Niemoeller1961] discussed the free-field calibration of microphones in the time domain. This method was standardized for 1-inch condenser microphones in 1974 [IEC1974] and the free-field correction (difference between free-field sensitivity and pressure sensitivity) of this type of condenser microphones was published in an IEC standard [IEC1979].

The last two decades have seen more advances in the developments of this method, which was implemented at several national metrology institutes. Gibbings and Gibson, from the National Laboratory of Australia, [Gibbings1984], discussed the free-field reciprocity calibration of 1-inch condenser microphones from 19.95 kHz to 316.5 Hz. In the USA, at the National Bureau of Standards (NBS), Burnett and Nedzelnitski [Burnett1987] described the calibration apparatus for free-field reciprocity calibration of condenser microphones, and gave the results of the calibration of 1-inch and ½-inch condenser microphones. At the Laboratoire National d'Essai (LNE) in France, Lambert and Durocher [Lambert1989] analyzed the problem of the realization of free-field conditions for the free-field calibration of 1-inch condenser microphones. K. Obermayr, A. Odin developed a measurement set-up for free-field reciprocity calibration the Physikalisch-Technische Bundesanstalt (PTB) in Germany [Obermayr1992a], where also Vorländer and Bietz extended the reciprocity calibration technique to diffuse field and introduced a broad-band reciprocity calibration method permitting the calculation of the impulse response of condenser microphones [Vorländer1993]. Richard Barham, from the National Physical Laboratory (NPL) in the UK [Barham1995], described the free-field calibration facilities built at the NPL, and gave his results for the sensitivity of ½-inch condenser microphones and the free-field correction of this type of condenser microphones. Facilities for free-field reciprocity calibration have also been developed in Japan [Miura1982] and Denmark [Rasmussen1993]. An international comparison of free-field reciprocity calibration of 1-inch and ½-inch condenser microphones of type LS1P and LS2P has been carried out between four European laboratories [Rasmussen1993].

Recently Barrera-Figueroa [Barrera-Figueroa2003] has developed a time selective technique to remove reflections from the time response of condenser microphones in order to improve the uncertainty of measurement for the free-field reciprocity calibration of condenser microphones.

Up to now, interest has been given to audio-frequency free-field reciprocity calibration. The existing standards for 1-inch and ½-inch condenser microphones calibration concern the audible frequency range. However, recently there has been an important increase of measurements in the ultrasonic frequency range, which require smaller condenser microphones (¼-inch microphones). But, the free-field reciprocity calibration for ¼-inch condenser microphones, which permits to obtain the free-field sensitivity in the ultrasonic frequency range, has not been developed yet.

I.5 Motivation of the project

I.5.1 Airborne ultrasound sources

Ultrasound is defined as sound vibrations propagated at frequencies above the upper limit of human hearing 20 kHz. It was first used by the military as SONAR for locating submarines during World War I. The idea was further expanded and used by the industry for therapy in the 1930s, and for flaw detection in the 1940s. Since World War II, great progress has been made in the development of new piezoelectric crystals, ferroelectric ceramics, and magnetrostrictive materials; applications of ultrasound have therefore increased considerably.

Today, exposure to airborne ultrasound occurs in several applications. Ultrasound devices are used in medicine, industry, consumer products, signal processing and testing. In daily life, we find various consumer-oriented devices, such as television remote controls, door openers, burglar alarms, traffic control devices, which are based on ultrasound. In the following, four examples of ultrasound applications are described in detail.

Plastic and metal welding

One of the oldest industrial applications of ultrasound is plastic welding (figure I-1.a). Ultrasound at frequencies between 20 kHz and 90 kHz is used to assemble toys, appliances, and thermoplastic parts. Sufficient heat is produced to melt the plastic in the required places. The principal advantages of this method are speed, easy automation, and welding in places, which are, difficult to access. Metal welding is used in the semiconductor industry for welding or micro-bonding miniature conductors. The process involves relatively low temperatures, usually below the melting point of the respective metal.

Ultrasonic scalpel

Over the last thirty years there has been an extensive use of ultrasound in medical applications, particularly in diagnosis, therapy and surgical applications. The example given in this paragraph concerns an ultrasonic surgical instrument used for cutting and coagulating: the HARMONIC SCALPEL® (figure I-1.b). This surgical device vibrates at 55,5 kHz blade denatures protein in the tissue to form a sticky coagulum. The pressure exerted on the tissue with the blade surface collapses blood vessels and allows the coagulum to form a hemostatic seal. The precision of cutting and coagulation is controlled by the surgeon by adjusting the power level, blade edge, tissue traction and blade pressure [HarmonicScalpel].

Parametric loudspeaker

A recent application of ultrasound is the parametric loudspeaker (figure I-1.c). This new type of audio system, unlike loudspeakers that spread sound everywhere, creates an extremely directive sound that travels in a narrow beam. The parametric loudspeaker uses the nonlinear behavior of air to create audio sound waves within the air itself by converting an ultrasonic set of frequencies of 40 kHz into audible sound [Bennett1975] [Blackstock1999] [Pompei1999].

Ultrasonic gas leak detector

Airborne ultrasound is used in the oil and gas industry for cleaning, gas leak detection, and other applications. This paragraph describes the ultrasonic gas leak detector (figure I-1.d). The traditional gas detection systems are based on a "sniffing" technology where the gas has to be in physical contact with the detector in order to be detected. Recently, a Denmark-based company, Innova Gassonic, has developed and marketed a new type of gas leak detector for fixed outdoor installations: a system based on airborne ultrasound emitted by the gas leak. When the ultrasonic gas leak detector triggers, the alarm indication will be raised at the speed of sound since the alarm will be active as soon as the detector "hears" the leak noise. Measurement tests have shown that the ultrasonic sound energy from a gas leak is located in the frequency range between 5 kHz and 50 kHz [Kornbech2005].

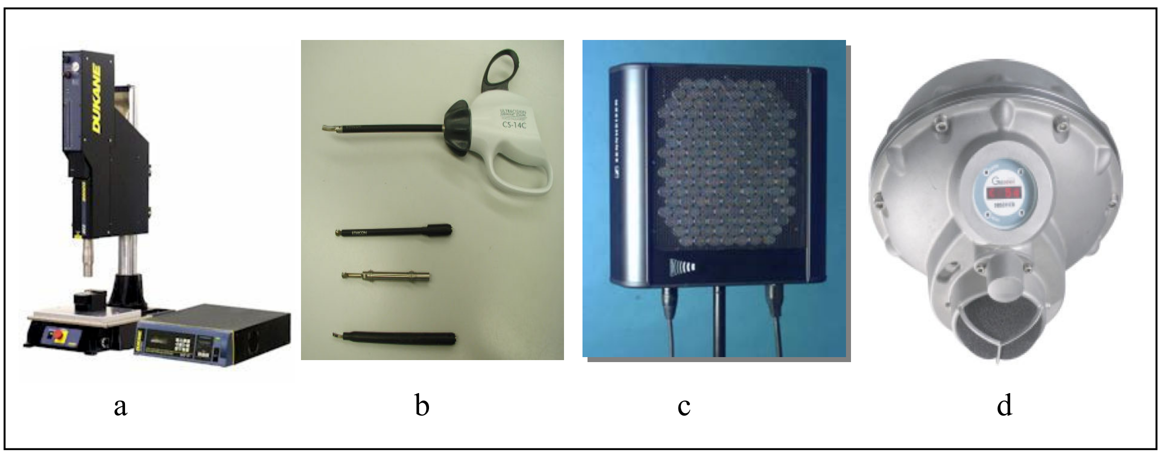


Figure I-1: Ultrasound applications: Plastic welding (a), ultrasonic scalpel (b), Parametric loudspeaker (c), Ultrasonic gas leak detector (d).

I.5.2 Effects of airborne ultrasound and exposure limits

The effects of high-level sound pressure of both audible and ultrasonic frequencies on humans are a problem of a complex nature. The effects of an exposure to airborne ultrasound can be divided into two categories: non-auditory effects including heating and cavitation, and auditory effects including effects on the central nervous system (called ‘‘subjective’’ effects) and damage to the ear.

In the last 50 years, several authors have investigated these effects:

Crawford (1955) wrote ‘‘when human beings are exposed to intense ultrasonic waves generated in air several characteristic effects are produced that vary somewhat depending on the subject. Using a high power siren it has been found that unusual fatigue is produced often accompanied by a loss of equilibrium and nausea. Other effects include a hammering sensation in the head near the ears and a disagreeable tickling in the mouth and nose. After a prolonged exposure, a headache may persist for some time, with some loss of hearing in the upper audible frequencies. These results are generally obtained at frequencies in the lower ultrasonic range, from 16-30 kc/s …’’ [Crawford1955].

Research indicates that airborne ultrasound has the potential to cause headache, fatigue and nausea [Acton1967] [Acton1974] [Hill1982] [IRPA1984] [Kryter1985] [Damongeot1985] [HC1991] [NOHSC2002] [OSHA2004] [HCP2004].

High-level Ultrasound often generates sub-harmonic frequencies in the audible frequency range. Research has shown that the eardrum vibrates nonlinearly and can generate sub-harmonics when exposed to high-level sound pressure [Dallos1966a] [Dallos1966b]. The amplitude of the sub-harmonics has the same order as the amplitude at the fundamental frequency and could damage the ear. It seems that these effects attributed to ultrasound were rather caused by energy at frequencies in the audible range [Acton1974] [Hill1982] [Kryter1985].

In order to control these effects, some guidelines on exposure limits have been developed in several countries [Damongeot1988] [HC1991] [NOHSC2002] [OSHA2004] [HCP2004]. A summary of the exposure limits is shown in table I-1 [Howard2005].

Frequency (kHz)	Exposure limit in dB ref 20 μPa proposed by						
	A	B	C	D	E	F	G
8	90	75					
10	90	75			80		
12.5	90	75	75		80		
16	90	75	85		80		75
20	110	75	110	105	105	75	75
25	110	110	110	110	110	110	110
31.5	110	110	110	115	115	110	110
40	110	110	110	115	115	110	110
50	110		110	115	115	110	110

Table I-1: Limits of the safe use of ultrasound proposed by A. Japan (1971); B. Acton (1974); C. USSR (1975); D. Sweden (1978); E. US Department of Defense (2004); F. International Radiation Protection Association (IRPA 1984); and G. Health Canada (1991).

I.6 Need for a primary standard at higher frequencies

Until now, there have been no internationally agreed limits for airborne exposure; in fact there is not enough information available concerning sound pressure levels produced by devices emitting airborne ultrasound, and only little is known about the possible harmful effects of the increasing use of ultrasound. In addition, before establishing appropriate limits and testing the output of ultrasound devices, there is a need for developing traceable sound pressure measurements in air in the frequency range from 20 kHz to about 160 kHz.

Current measurement standards for airborne ultrasound are realized by means of the sensitivity of ½-inch laboratory standard microphones, calibrated with the reciprocity method in the frequency range from 20 kHz to 40 kHz. Sound fields are usually quantified in terms of sound pressure level (SPL), in decibels (dB):

$$\text{SPL (dB)} = 20 \log10 (P/P_{\text{ref}})$$

where P is the acoustic pressure in air under free-field conditions. The reference pressure P_{ref} = 20 μPa, which is approximately the lowest intensity of audible sound perceived by human subjects at 1 kHz. The actual decibel levels in an airborne ultrasound field can be determined with sound level meters, which normally include ½-inch working standard microphones. The ½-inch microphone has a limited frequency range, with a maximum frequency of 40 kHz.

One possibility permitting the measurement of ultrasound in air in the low frequency range from 20 kHz to 160 kHz, is the use of ¼-inch condenser microphones, but at present, there is no primary calibration method for this type of condenser microphones. The aim of the work described in this thesis is the development of a primary free-field calibration technique for ¼-inch condenser microphones in the frequency range from 20 kHz to 160 kHz by using the reciprocity method.

I.7 Contents of the thesis

This thesis is divided into six chapters, including this general introduction.

After this general introduction, which describes the state of the art of free-field reciprocity calibration of condenser microphones, and discusses the motivation and the aim of this thesis, chapter II deals with the theory of the reciprocity calibration of condenser microphones, and discusses difficulties in the experimental implementation of this technique. It first introduces the theoretical operation of condenser microphones, and discusses the application of the reciprocity principle to the primary calibration of condenser microphones, and finally describes the transfer function between two microphones in the free field, which contains the product of the free-field sensitivity of the two microphones. The expression of the sensitivity of each microphone can be derived from three pair-combinations of three microphones. This chapter will also discuss practical considerations of this method: the attenuation of sound pressure in air, interaction between transmitter and receiver microphones, effective distance between microphones, distortion of the driving voltage of the transmitter microphone, and the effects of environmental conditions on the free-field sensitivity of condenser microphones.

Chapter III is dedicated to the development of a new automated measurement set-up for the free-field reciprocity calibration of ¼-inch condenser microphones, the results obtained are discussed in detail.

In chapter IV an approach for the determination of the uncertainty of the free-field sensitivity is discussed.

Chapter V describes the use of a time-selective technique permitting the identification of disturbances due to crosstalk, standing waves and reflections and the possibility of their elimination.

Chapter VI draws conclusions to the thesis work and contains proposals for the future research to improve free-field reciprocity calibration of condenser microphones.

CHAPTER II

RECIPROCITY CALIBRATION OF CONDENSER MICROPHONES THEORY AND PRATICE

II-1 Introduction

This chapter deals with the reciprocity calibration of condenser microphones in theory and practice. It describes the theoretical basis for the application of the reciprocity principle to the primary calibration of condenser microphones, and the practical implementation of the theory. It also discusses difficulties in confirming experimental conditions regarding the assumptions on which the theory is based.

II.2 The condenser microphone

A transducer is a device that transforms energy from one form to another. In the case of a microphone, acoustic energy is converted into electrical energy. Microphones are based on a number of transduction principles (electrostatic, piezoelectric, magnetic, and electrodynamic), and are built according to specific requirements. Their applications can be divided into three main classes [Encyclopedia1997]:

- *Communication microphones used for speech communication, such as: telephone microphones and hearing aids.*
- *Sound recording and broadcasting microphones, intended for the reproduction of speech and music.*
- *Measurement microphones used for the measurement of acoustic pressure.*

In this work the focus is placed on condenser microphones, which are precise transducers, used in acoustics for accurate airborne sound measurements. Condenser microphones are used for the calibration of acoustical instruments and for the realization of the unit of sound pressure; Pascal, because of the following properties [B&K1996]:

- *Wide linear dynamic range, low noise and distortion.*
- *Flat frequency response.*
- *Low influence of the environmental conditions: temperature, static pressure, and electromagnetic fields.*
- *High stability and good mechanical robustness*
- *Simple design suitable for calibration*

A condenser microphone is a parallel plate capacitor formed by a membrane and a back plate located very close behind (figure II.1). The diaphragm and back plate are electrically insulated from each other. The internal static pressure is equalized by means of a small vent hole in the housing of the microphone. When the microphone is exposed to a sound pressure, the diaphragm undergoes an alternative force proportional to the pressure and the diaphragm area. The movement of the diaphragm varies the capacity, and these variations are converted into an alternating voltage if a constant charge is present between the electrodes (diaphragm and back plate).

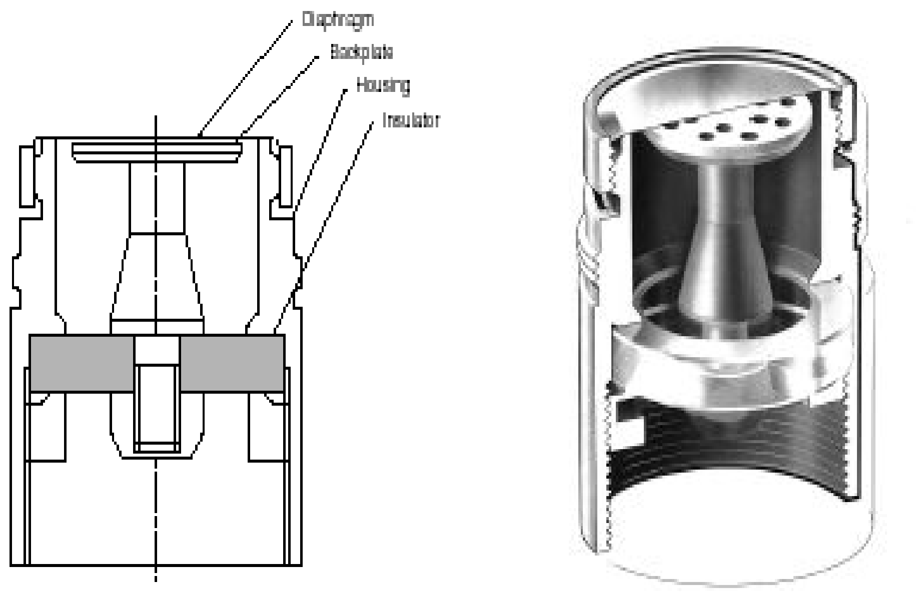


Figure II.1: Classic design of a condenser microphone (From [B&K1996]).

II.3 Condenser microphones and reciprocity

II.3.1 Acoustic reciprocity

In physics, reciprocity is a powerful concept, playing a major role in obtaining some general results. It describes how a system behaves when one parameter of the system is reversed. Helmholtz [Helmholtz1860] and Rayleigh [Rayleigh1896] developed the concept of acoustic reciprocity. The principle of reciprocity states that:

If a pressure p at one point causes a volume velocity U at a second point B, then the same pressure at the second point B will cause an equal volume velocity U at the first point A.

The reciprocity relation can be derived by the application of Green's theorem to the Helmholtz wave equation. The theorem of acoustic reciprocity is:

If harmonic irrotational vibrations of small amplitude are propagated in a medium of uniform density and an excess pressure p_1 produces a particle velocity u_1, and similarly p_2 produces u_2, then the surface integral

$$\int (u_2 p_1 - u_1 p_2)\, ds = 0 \qquad \text{(II.1)}$$

where the integration is taken over the boundaries of the volume.

A medium fulfilling the Helmholtz wave equation is reciprocal, and linear dissipative phenomena do not upset this reciprocity [Lamton1984].

II.3.2 Acoustic reciprocity and point sources

By applying the theorem of acoustic reciprocity in the case of point sources, general properties of these sources can be derived.

According to [Kinsler2000], let there be a region of space in which two irregularly shaped sources are located, as shown in figure II.2. Let a source A be active and source B be perfectly rigid in situation 1, and vice versa in situation 2.

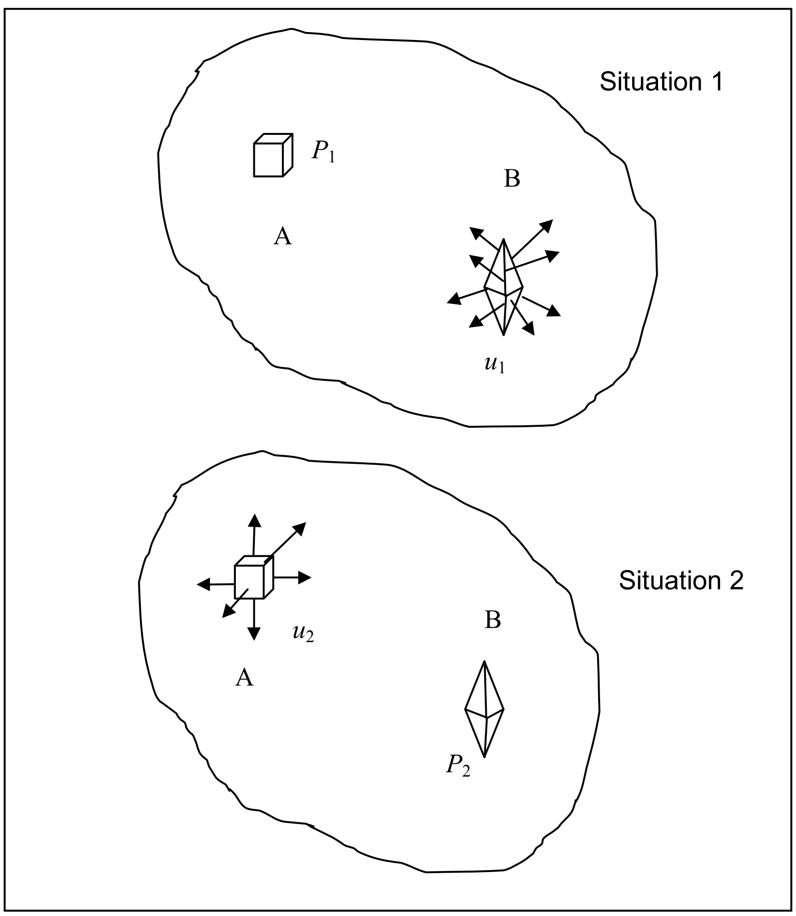


Figure II.2: Reciprocity theorem applied to simple source.

Let p_1 be the pressure at B when the source A is active with u_1 being the velocity of its radiation element, and p_2 be the pressure at A when the source B is active with u_2 being the velocity of its radiating element.
The application of eq. (II.1) yields to:

$$\int_{S_A} (u_1 p_2)\ ds = \int_{S_B} (u_2 p_1)\ ds \tag{II.2}$$

In the case of point sources, and for large distances (several wavelengths) between source A and B, the pressure is uniform over each source, then

$$\frac{1}{p_1}\int_{S_A} u_1\ ds = \frac{1}{p_2}\int_{S_B} u_2\ ds \tag{II.3}$$

By assuming that the radiating element of the source has a complex vector displacements

$$\vec{\xi} = \left|\vec{\mathrm{E}}\right| e^{j(\omega t+\varphi)} \tag{II.4}$$

where
$\left|\vec{\mathrm{E}}\right|$ is the magnitude and direction of the displacement, ω is the pulsation, *t the time, and* φ the temporal phase of each element.
The complex volume displaced by the source is given as

$$\zeta = \int_{s} \left|\vec{\mathrm{E}}\right| e^{j(\omega t+\varphi)}\ \vec{n}\ ds = V e^{j(\omega t+\theta)} \tag{II.5}$$

where V is the volume displacement amplitude, and θ the accumulated phase over the surface of the element.
The time derivative of the volume displacement defines the complex source strength Q

$$Q\ e^{j\omega t} = \frac{\partial V}{\partial t} = \int_{S} \vec{u}\ \vec{n}\ ds \tag{II.6}$$

where $\vec{u} = \dfrac{\partial \vec{\xi}}{\partial t}$ is the complex velocity distribution of the source surface.
In the case of a pulsating sphere of radius *a*, vibrating radially with a complex speed $U_0 e^{jwt}$, the real part of the source strength Q can be given by:

$$Q = 4\pi a^2 U_0 \tag{II.7}$$

The substitution of (II.6) and $p = P(r)\, e^{j(\omega t - kr)}$ into (II.3) yields

$$\frac{Q_1}{P_1(r)} = \frac{Q_2}{P_2(r)} \qquad \text{(II.8)}$$

This equation shows that the ratio of the source strength to the pressure amplitude at a distance *r* from the source is the same for all simple sources at the same frequency in the same surroundings.

II.3.3 Acoustic reciprocity and transducers

The reciprocity principle takes an important place in the foundation of electroacoustics theory and practice. It helps understand the fundamentals of electromechanical coupling, and results in a pertinent technique for the absolute calibration of transducers. Theorems for electroacoustic transducers go back to W. Shottky [Shottky1926], and have been discussed and described in detail by L. L. Foldy and H. Primakoff [Foldy1945] [Foldy1947]. A model of a linear electroacoustic transducer can be developed by treating a transducer as a two-port network that relates electrical quantities at one port to mechanical quantities at the other (figure II.3). These quantities are given as

E: the voltage across the electrical inputs to the transducer
I: the current at the electrical inputs
P: the pressure on the radiating surface
U: the volume velocity of the radiating surface

The electrical port characterized by current *I* and voltage *E*, the product *EI* represents the electric power input. And for the other port characterized by the volume velocity *U* representing the time rate of change of the volume enclosed by the surface, and by the pressure over the surface of the transducer *P*, the product *PU* is the mechanical power input to the transducer.

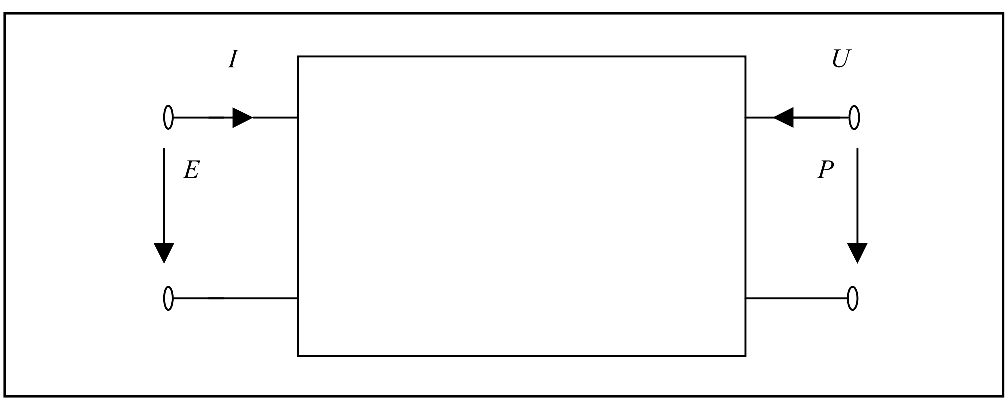


Figure II.3: Two-port representation of an electroacoustical transducer.

When all variables (P, U, E, and I) vibrate at the same frequency f, the physical proprieties of a linear transducer lead to two algebraic relations, called canonical equations that can be written as

$$\begin{bmatrix} E \\ P \end{bmatrix} = \begin{bmatrix} Z_{ec} & T_{ea} \\ T_{ae} & Z_a \end{bmatrix} \begin{bmatrix} I \\ U \end{bmatrix} \qquad \text{(II.9)}$$

where
Z_{ea} is the clamped electrical impedance (equal to E/I when U is zero), and
Z_a the open-circuit impedance (equal to P/U_{out} when I is zero).

A transducer is reciprocal if T_{ea}=T_{ae} (T_{ea} is called the transduction coefficient). In this case, the generalized velocity (U or I) at one side of the transducer results from an application of a generalized force (P or E) on the other side has the same direct proportionality to this force as when the locations of generalized force and generalized velocity are interchanged, i.e.,

$$(\frac{U}{E})_{P=0} = (\frac{I}{P})_{V=0} \qquad \text{(II.10)}$$

This is a reciprocity principle analogous to the principle discussed in the part concerning the reciprocity of an acoustic system.

Several electroacoustic transducers follow this principle such as piezoelectric, piezoceramic, and electrostatic transducers [Kinsler2000]; as a consequence their sensitivity as receivers is equal to their sensitivity as transmitter. Some electroacoustic transducers are antireciprocal, as, for example, magnetostrictive, moving-coil transducers, which due to magnetic laws are not time invariant but reversing direction, and as a consequence, their sensitivity as transmitters and receivers is equal in amplitude but with opposite phase [Lamton1984]. Other transducers are not reciprocal and not antireciprocal as for example the carbon microphone used in telephones [Richardson1953].

II.3.4 Reciprocity equations of condenser microphones

Condenser microphones are electrostatic transducers following the principle of reciprocity. Ballatine [Ballatine1929] suggested firstly the application of reciprocity in the calibration of condenser microphones, and then it was used for the free-field calibration of condenser microphones by McLean [MacLean1940] and for pressure field by Cook [Cook1940]. A simple model describing the principle of its operation is described here.
Condenser microphone can be modeled as a parallel plate capacitor, one plate held stationary, and the other, the diaphragm, moving under mechanical or electrical excitation.

The condenser microphone is connected to an electrical circuit as shown in figure II.4, where E_0 is the polarizing voltage, *R* is a resistance of high value, and *E* is the output voltage of the microphone (used as receiver) or the applied driving voltage when used as transmitter.

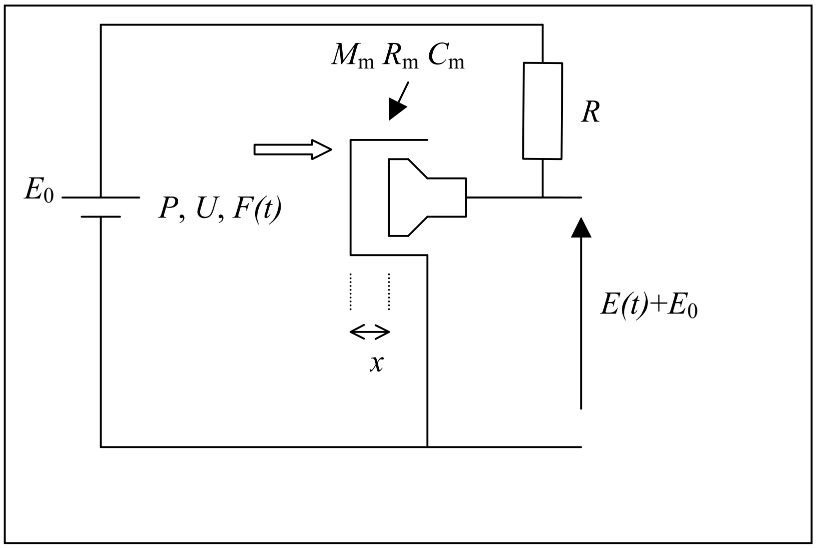


Figure II.4: Mechanical and electrical model of the microphone.

F is the force acting on the diaphragm characterized by the mechanical mass M_m, mechanical compliance C_m, and resistance R_m.
In the assumption of a parallel plate capacitor, the capacity of the condenser microphone is $C_1=\varepsilon S/x_1$, when the microphone is polarized, and $C_0=\varepsilon S/x_0$ when the microphone is not polarized, where

ε is the permittivity of the material between the plates (air).
S is the surface of the diaphragm
x_1 is the distance between the plates when the microphone is polarized
x_0 is the distance between the plates when the microphone is not polarized

At static equilibrium mechanical and electrostatic forces are equal, thus

$$(x_1 - x_0)/C_m = q_0^{\ 2}(2C_0 x_0) \qquad \text{(II.11)}$$

When a force F is acting on the diaphragm, the separation is $x = x_0 + x(t)$ and the charge on the microphone is $q = q_0 + q(t)$. The dynamic microphone capacitance is

$$C = \frac{\varepsilon S}{x_0 + x(t)} = \frac{C_0}{1 + \dfrac{x(t)}{x_0}} \qquad \text{(II.12)}$$

The equation of the diaphragm motion is given by

$$-F(t) = M_m \frac{\partial^2 x}{\partial t^2} + R_m \frac{\partial x}{\partial t} + \frac{(x - x_1)}{C_m} + \frac{q^2}{2Cx} \qquad \text{(II.13)}$$

From Eq. (II.11)

$$\frac{x - x_1}{C_m} = \frac{x(t) + x_0 - x_1}{C_m} = \frac{x(t)}{C_m} - \frac{{q_0}^2}{2C_0 x_0} \qquad \text{(II.14)}$$

From Eq. (II.12)

$$\frac{q^2}{2Cx} = \frac{(q_0 + q(t))^2 (1 + \dfrac{x(t)}{x_0})}{2C_0 (x_0 + x(t))} \approx \frac{{q_0}^2 (1 + \dfrac{q(t)}{q_0})}{2C_0 x_0} \qquad \text{(II.15)}$$

Substituting (II.14) and (II.15) in (II.13), the equation of the diaphragm motion becomes

$$-F(t) = M_m \frac{\partial^2 x}{\partial t^2} + R_m \frac{\partial x}{\partial t} + \frac{x(t)}{C_m} + \frac{q_0 q(t)}{2C_0 x_0} \qquad \text{(II.16)}$$

If the applied force varies as e^{jwt} so that the diaphragm velocity will be

u=dx/dt=$j\omega x$, and the electric current I=dq/dt=$j\omega q$

Substituting these two parameters into (II.16), it becomes

$$-F(t) = -u(j\omega M_m + \frac{1}{j\omega C_m}) + I(\frac{q_0}{j\omega C_c x_0}) \qquad \text{(II.17)}$$

This can be written as following:

$$-F(t) = I(\frac{q_0}{j\omega C_c x_0}) + Z_{me}u \tag{II.18}$$

where Z_{me} is the mechanical impedance of the microphone when the electrical terminal is unloaded; I=0.

By application of Kirchhoff's rule to the electrical circuit in figure II.4

$$\frac{q}{C} + R\frac{\partial q}{\partial t} = E_0 + E(t) = \frac{q_0}{C_0} + E(t) \tag{II.19}$$

and under the assumption of small displacements from equilibrium, q(t)x(t) is negligible, so

$$\frac{q}{C} = \frac{(q_0 + q(t))(1 + \frac{x(t)}{x_0})}{C_0} = \frac{q_0}{C_0} + \frac{q(t)}{C_0} + (\frac{q_0 x(t)}{x_0 C_0}) \tag{II.20}$$

Thus, Eq. (II.19) can be written as

$$E(t) = R\frac{\partial q}{\partial t} + \frac{q(t)}{C_0} + \left(\frac{q_0 x(t)}{x_0 C_0}\right) \tag{II.21}$$

In the case of a sinusoidal variation, this equation becomes:

$$E(t) = R\frac{\partial q}{\partial t} + \frac{1}{jC_0\omega}\frac{\partial q}{\partial t} + \frac{q_0}{jC_0\omega x_0}\frac{\partial x}{\partial t} \tag{II.22}$$

So

$$E(t) = I\left(R + \frac{1}{jC_0\omega}\right) + u\left(\frac{q_0}{jC_0 x_0 \omega}\right) \tag{II.23}$$

this can be written as

$$E(t) = Z_e I + \left(\frac{q_0}{jC_0 x_0 \omega}\right)u \tag{II.24}$$

where Z_e is the electrical impedance of the microphone when the diaphragm is blocked u=0.

By using the relation between sound pressure P and force F; P=F/S, and the relation between volume velocity U and velocity u; U=-uS.

Equations (II.18) and (II.24) become

$$P = Z_a U + T_{ae} I \tag{II.25}$$

$$E = T_{ea} U + Z_e I \tag{II.26}$$

where $Z_a = Z_m/S$ is the acoustic impedance of the microphone.

$T_{ae}=T_{ea}=T=q_0/(j\omega S C_0 x_0)$ is called transduction coefficient, describing the electroacoustic reciprocity of the microphone. The transduction coefficient can be indicated as $T= \phi/(j\omega C_0)$, where $\phi=q_0/(Sx_0)$, which is real and independent of frequency, considered as a characteristic of the microphone describing the transduction mechanism. These two equations are called the two-port equations of the microphone, describing the interaction between the electrical and the acoustical side (port) of the microphone, and constitute a basis for the reciprocity calibration of microphones.

II-4 Condenser microphone as receiver

In free-field conditions, the sensitivity of a condenser microphone is given as the ratio of the output voltage to the sound pressure at the acoustic center of the microphone before the microphone is introduced to the field.

Let a condenser microphone be placed in the progressive plane wave of a sound pressure p_0, the equivalent circuit for a receiving microphone under free-field conditions is represented in figure II.5, where:

P_0' is the sound pressure acting on the blocked diaphragm, P is the sound pressure at the acoustic terminals of the microphone, and $Z_{a,r}$ is the acoustic radiation impedance.

P_0' is related to P_0 through the scattering factor σ:

$$P_0' = \sigma(f, \theta) P_0 \tag{II.27}$$

The scattering factor σ is a function of frequency f and angle of incidence of the sound wave acting on the microphone diaphragm θ, and depends on the geometrical configuration of the microphone.

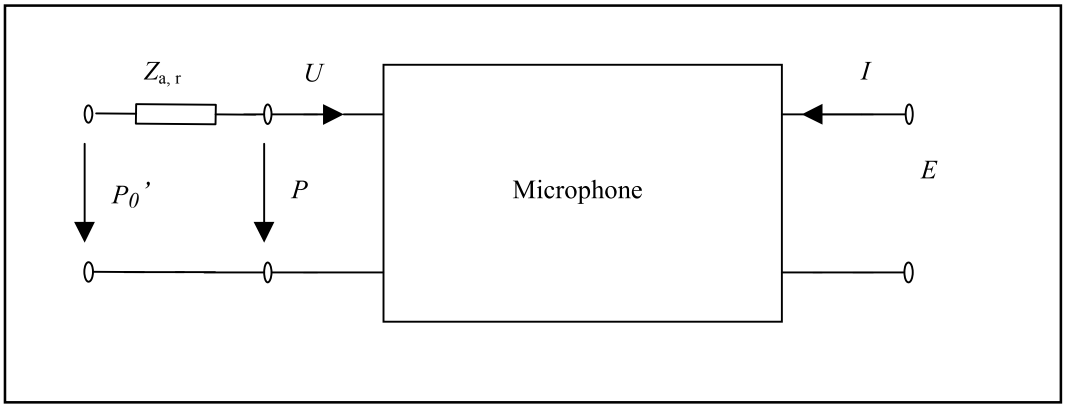


Figure II.5: Equivalent circuit for a receiver microphone under free-field conditions.

From the equivalent circuit (figure II.5), it can be deduced that:

$$P = P_0' - Z_{a,r} U \tag{II.28}$$

The two-port equations (II.25) and (II.26) can be written as:

$$E = Z_e I + TU \tag{II.29}$$

$$P_0' = \sigma P_0 = TI + (Z_a + Z_{a,r})U \tag{II.30}$$

Thus, from the definition, the free-field sensitivity M_f of the microphone is given by:

$$M_f = \left(\frac{E}{p_0}\right)_{I=0} = \frac{T}{Z_a + Z_{a,r}} \sigma(f, \theta) \tag{II.31}$$

II.5 Condenser microphone as sound source

Figure II-6 shows the equivalent circuit of the condenser microphone when used as a transmitter. Let u_0 be the volume velocity of a point source located at the acoustic center of the microphone (transmitter).

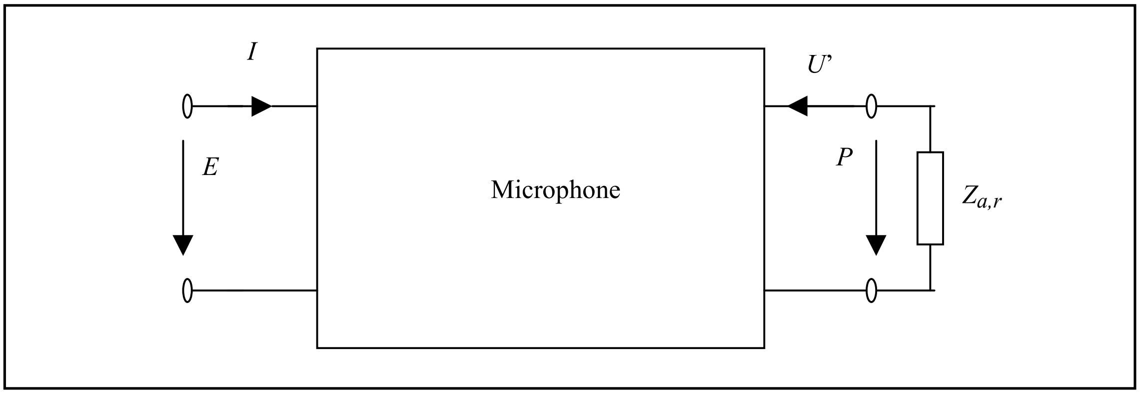


Figure II.6: Equivalent circuit for transmitter microphone under free-field conditions.

The pressure at the diaphragm of the microphone is given by:

$$P = -Z_{a,r}U' \tag{II.32}$$

The two-port equations of the microphone can be written as:

$$E = Z_e i + TU' \tag{II.33}$$

$$0 = TI + (Z_a + Z_{a,r})U' \tag{II.34}$$

Thus, the volume velocity can be obtained as:

$$-U' = \frac{T}{Z_a + Z_{a,r}} I \tag{II.35}$$

Let *U* be the volume velocity of a point source equivalent to the microphone placed in a free field. By considering the microphone as a point source and taking into account the acoustic reciprocity property in the case of point source in free field, the relation between *U* and *U*' can be deduced.

Figure II.7 shows a point source of volume velocity *U* produces a sound pressure P_0 in free field at a receiver point positioned at a distance *r* from the point source (case 1, situation 1). This point source generates a sound pressure P'_0 at the microphone placed at the same distance *r* from the source (case 1, situation 2).

In the case (2), the microphone now is used as a transmitter with a volume velocity *U*' produces a sound pressure P_b in the free field at a point receiver placed at a distance *r* (situation 2). Let U_b the volume velocity of the point source which could produce this sound pressure (P_b) when used in the place of the microphone (situation 1).

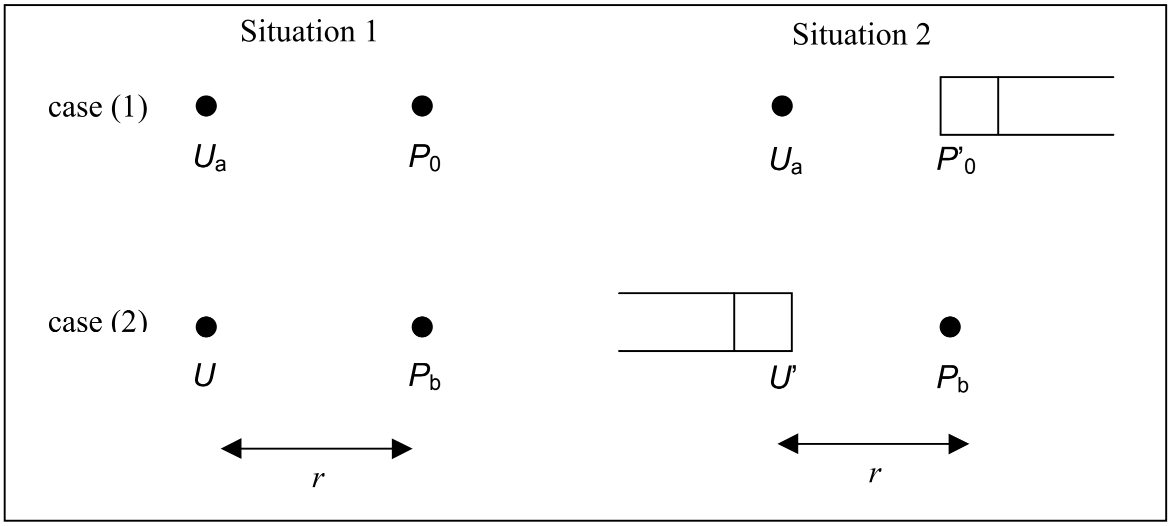


Figure II. 7: Situations when the microphone is represented by an equivalent point source.

From the acoustic reciprocity of the point source and the point receiver placed in free field (situation 1)

$$\frac{U_a}{P_0} = \frac{U}{P_b} \qquad \text{(II.36)}$$

and from the situation 2

$$\frac{U_a}{P'_0} = \frac{U'}{P_b} \qquad \text{(II.37)}$$

the division of (II.37) and (II.36) defines the relation between *U* and *U'* as:

$$\frac{U}{U'} = \frac{P_0'}{P_0} = \sigma(f,\theta) \qquad \text{(II.38)}$$

So, (II.35) can be written as:

$$-U = \sigma(f,\theta)\frac{T}{Z_a + Z_{a,r}} I \qquad \text{(II.39)}$$

The free-field sensitivity of the microphone used as transmitter is defined as the quotient of the open-circuit volume velocity (zero loads) of the microphone by the driving current of the microphone, given by the following formula:

$$M_f = \left(\frac{-U}{I}\right)_{P=0} = \sigma(f,\theta)\frac{T}{Z_a + Z_{a,r}} \qquad \text{(II.38)}$$

which is the same as the free-field sensitivity of the microphone used as a receiver.

II.6 Transfer function between two microphones in free field

After description of the condenser microphone used in both cases of its operation (transmitter and receiver), let us now consider the case of two microphones placed in free field. One microphone is used as transmitter, the other as a receiver.

If the transmitter microphone is considered as a point source radiating into an open space, the generated sound pressure is given by solving the wave equation, given, in the case of spherical coordinates by

$$\frac{\partial^2 P_0}{\partial r^2}+\frac{2}{r}\frac{\partial P_0}{\partial r}+\frac{1}{c^2}\frac{\partial^2 P_0}{\partial t^2}=0 \qquad \text{(II.39)}$$

where c is the wave velocity.
The solution of the wave equation is given by

$$P_0=\frac{A}{r}e^{j(\omega t-kr)} \qquad \text{(II.40)}$$

where
A is the amplitude, K the complex wave number given by $K=k-j\alpha$, and α the attenuation of air.
The particle velocity of the transmitter microphone can be derived from the momentum equation

$$\frac{\partial u}{\partial t}=\frac{-1}{\rho}\nabla p \qquad \text{(II.41)}$$

where ρ is the air density. For spherical waves, the volume velocity is related to the velocity by

$$U=4\pi r^2 u \qquad \text{(II.42)}$$

Thus,

$$\frac{\partial U}{\partial t}=\frac{-4\pi r^2}{\rho}\frac{\partial}{\partial r}\left(\frac{A}{r}e^{j(\omega t-Kr)}\right) \qquad \text{(II.43)}$$

$$U=\frac{4\pi}{j\omega\rho}\left[Ae^{j(\omega t-kr)}+\frac{Ar}{c}e^{j(\omega t-Kr)}\right] \qquad \text{(II.44)}$$

The transmitter volume velocity is obtained by using the limit $r\to 0$

$$U(0) = \frac{4\pi}{j\omega\rho} A e^{j\omega t} \qquad \text{(II.45)}$$

Therefore, the ratio of the pressure at a distance *d* from the microphone transmitter to the transmitter microphone volume velocity is given by

$$\frac{P(d)}{U(0)} = \frac{j\omega\rho}{4\pi d} e^{-kd} e^{-\alpha d} \qquad \text{(II.46)}$$

This ratio is called acoustic transfer impedance.
The pressure at the receiver microphone *P* and the volume velocity of the transmitter microphone *U* are related to the sensitivities of the transmitter microphone $M^a{}_f$ and the receiver microphone $M^b{}_f$

$$U = M_f{}^a I \qquad \text{(II.47)}$$

$$E = M_f{}^b P \qquad \text{(II.48)}$$

So, *E* can be written as:

$$E = M_f{}^b M_f{}^a I \frac{j\omega\rho}{4\pi d} e^{-\alpha d} e^{-jkd} \qquad \text{(II.49)}$$

Thus, the magnitude of the product sensitivity of the two microphones can be expressed as follows

$$\left| M_f{}^b M_f{}^a \right| = \frac{2d_{ab}}{\rho f} e^{-\alpha d} \left(\frac{E}{I} \right) \qquad \text{(II.50)}$$

where d_{ab} is the distance between the acoustic centers of transmitting and receiving microphones.

From this equation, it can be seen that the sensitivity product of two microphones coupled in free field can be calculated from the electrical transfer impedance, the effective distance between the microphones and the characteristics of the air. This equation constitutes the basis of the reciprocity technique.

By using three microphones, three expressions for the sensitivity product of the pairs of microphones can be calculated, and thus, an individual sensitivity can be derived for each microphone.

II.7 Practical considerations

The free-field reciprocity calibration of microphones permits the determination of the sensitivity of the microphone by measuring the acoustic transfer impedance and the electrical transfer impedance between the microphones. The accuracy of the measured free-field sensitivity of the microphone depends on practical difficulties in confirming experimental conditions regarding the assumptions on which the theory of reciprocity calibration is based, as well as the characteristics of the microphones and the set-up used in the calibration. In order to make a precise calibration, these sources of uncertainty must be controlled.

II.7.1 Attenuation of sound in air

The attenuation of sound plays an important role in the free-field calibration of microphones. Several studies have been carried out to permit its calculation; K. Rasmussen has reported the latest results in literature [Rasmussen1997].

When a spherical sound wave travels through the air, its amplitude diminishes with distance, due to the geometric attenuation, the attenuation of energy by viscous and thermal effects called ‘’classical attenuation’’, and molecular attenuation due to internal relaxation.

The geometrical attenuation does not come from energy dissipation, the amplitude of sound decreases with distance because of the distribution of the energy over a large volume. The energy density of a spherical wave decreases proportionally to the squared radius.

The classic attenuation is based on the viscosity and thermal conduction of the air. Viscosity occurs when there is a relative motion between adjacent portions of air due to the compression and expansion accompanying the transmission of the sound wave; the energy lost is converted to heat. The thermal attenuation results from the conduction of thermal energy from the regions of higher temperature to those of lower temperature. The molecular attenuation results from the conversion of kinetic energy (transnational energy) into internal energy of molecules, including rotational and vibrational energies [Kinsler2000].

The sound pressure attenuation coefficient due to viscosity is a function of the coefficient of viscosity η, the density of air ρ, the sound speed of air c, and the angular frequency ω. The sound pressure attenuation coefficient due to thermal conduction increases with the squared frequency. It depends on the specific heat at constant pressure C_p, the thermal conductivity κ, and the ratio of specific heat γ. The classic attenuation, which combines both the viscous and the thermal attenuation, is given by the formula [BASS1984] [Kinsler2000]

$$\alpha_C = \alpha_V + \alpha_T = \frac{\omega^2}{2\rho c^3}\left(\frac{4\mu}{3} + \frac{(\gamma-1)\kappa}{C_p}\right) \quad \text{(II.51)}$$

This formula can be written as function of frequency, temperature, and static pressure as [Bass1984]

$$\alpha_C = 5.578\times 10^{-9}\,\frac{T/T_0}{T+110.4}\,f^2\left(\frac{P_{S,R}}{P_S}\right) \quad \text{(II.52)}$$

By taking into account the rotational relaxation attenuation, sum of the classic attenuation and the rotational relaxation attenuation is given by

$$\alpha_{CR} = \alpha_C + \alpha_R = 1.84\times 10^{-11}\,\frac{(T/T_0)^{1/2}}{(P_S/P_{S,R})}\,f^2 \quad \text{(II.53)}$$

According to the standard ISO 9613-1 [ISO1993], when considering vibrational relaxation attenuation, the total sound pressure attenuation coefficient can be given by the equation

$$\alpha = \alpha_C + \alpha_R + \alpha_V = f^2\left[\begin{array}{l} 1.84\times 10^{-11}\dfrac{(T/T_0)^{1/2}}{(P_S/P_{S,R})} \\ +\left(\dfrac{T}{T_0}\right)^{-5/2}\left(0.01275\dfrac{e^{-2239.1/T}}{f_{rO}+f^2/f_{rO}} + 0.1068\dfrac{e^{-3352.0/T}}{f_{rN}+f^2/f_{rN}}\right)\end{array}\right] \quad \text{(II.54)}$$

where f_{rO} is the relaxation frequency of oxygen and f_{rN} is the relaxation frequency of nitrogen, given by the formulas

$$f_{rO} = \frac{P_S}{P_{S,R}}\left[24 + 4.04\times 10^6 x_w\left(\frac{0.2+10^3 x_w}{3.91+10^3 x_w}\right)\right] \quad \text{(II.55)}$$

$$f_{rN} = \frac{P_S}{P_{S,R}}\left(\frac{T}{T_0}\right)^{-1/2}\left[9 + 28.0\times 10^3 x_w e^{\left(-4.170\left(\left(\frac{T}{T_0}\right)^{-1/3}-1\right)\right)}\right] \quad \text{(II.56)}$$

where x_w is the mole fraction of water vapor in air (see Annex…).
Figure II.8 shows numerical results of the attenuation of sound pressure calculated by the formula (II.54) as function of frequency under normal environmental conditions (T=23°c, P=101.325 kPa, H=50%). The attenuation increases with the frequency, up to approx. 9 dB/m at 200 kHz.

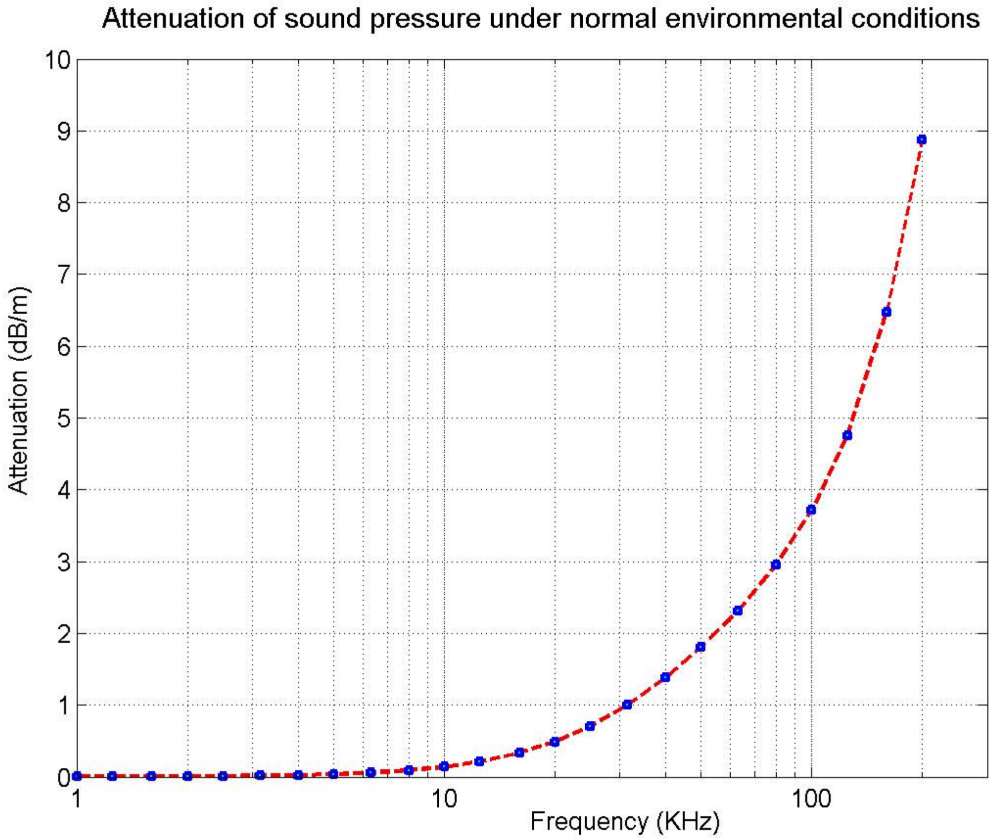


Figure II.8: Sound pressure attenuation as a function of frequency under normal environmental conditions (T=23°c, P=101.325 kPa, H=50%).

II.7.2 Interaction between transmitter and receiver microphones

One assumption underlying the theory of free-field reciprocity calibration of microphones is that there is no interaction between transmitter and receiver microphones. But, in practice, interactions exist and result in two types of interferences: standing waves, due to the reflection of the direct signal by the receiver and the transmitter microphones, and crosstalk which is an electric signal that is unintentionally transmitted from the transmitter microphone to the receiver microphone, bypassing the acoustic path.

A wave interference signal (crosstalk or standing waves) travels on a path different from that of the direct signal being measured, and differs in amplitude and phase, but has the same frequency as the direct signal (figure II.9).

If two waves from the same source travel on paths that differ by the distance x, their phase difference at the end of the paths will be $2\pi fx/c$.
where f is the frequency, and c the speed. If x is some odd number of half-wavelength, the waves will interfere destructively, but if x is some number of whole

wavelengths, the waves will interfere constructively. As the frequency changes, the waves alternately add and subtract, resulting in an oscillation of frequency interval $\delta f = c/x = c/d$ for crosstalk, and $\delta f = c/x = c/2d$ for standing waves, where d is the distance between the transmitter and the receiver microphones.
For a single frequency and as function of distance, the interference results in an oscillation of $\delta x = \lambda$ for crosstalk, and $\delta x = \lambda/2$ for standing waves (where λ is the wavelength).
Standing waves between the microphones require that the diameter of the microphones is large enough compared to the wavelength, to be good reflectors. As a consequence, standing waves occur at higher frequencies. However, crosstalk is generally independent of amplitude of the acoustic signal, therefore, if crosstalk occurs, it will be more evident at lower frequencies, where the acoustic signal is low. These characteristics of interference facilitate its identification and minimization when designing the measurement set-up for free-field reciprocity calibration of microphones.

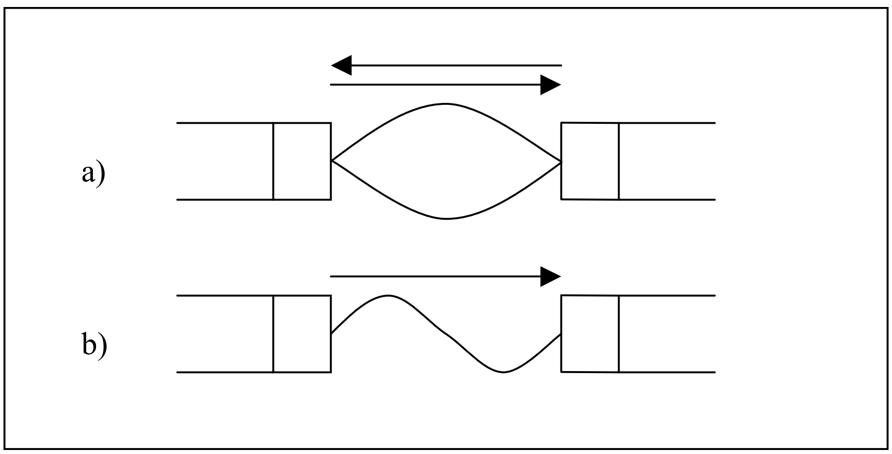


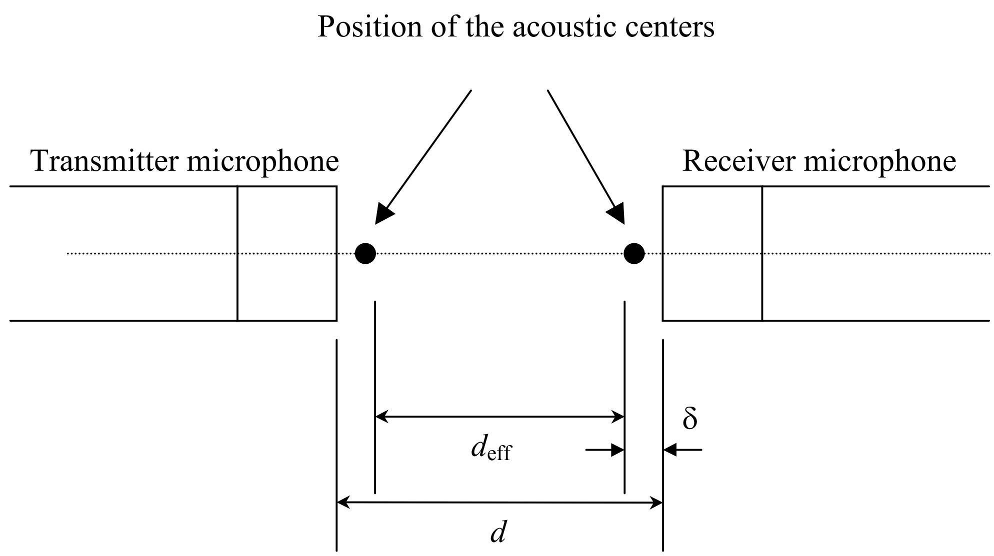
Figure II.9: Wave interference between transmitter and receiver microphones. a) standing waves, b) crosstalk.

II.7.3 speed of sound and density of air

The density and the speed of sound play an important role in acoustics and have been investigated since the earliest acoustic measurements. Experimental and numerical methods for their determination still interest researchers, for improvements of the measurement techniques, and the reduction of uncertainties. The primary free-field calibration of microphones requires precise values of the air density and the speed of sound, which permit the calculation of the acoustical transfer impedance. K. Rasmussen reported the latest results in the literature and recommended a specific procedure for calculating the density and the speed of sound [Rasmussen1997].
In this work the values of the speed of sound and the density of air were calculated according the formulas given by k. Rasmussen in the report [Rasmussen1997].

II.7.4 Effective distance between microphones

The free-field reciprocity equation is based on the assumption that both transmitter and receiver microphones are point sources. The effective distance between transmitter and receiver microphones is defined as the distance between the equivalent points located at the acoustic center of transmitter and receiver microphones. Under this, as well as under free-field conditions, the pressure is proportional to the inverse distance; as a consequence, the output voltage corrected for absorption is proportional to the inverse distance. The position of the acoustic center of a microphone can be determined via the distance axis offset of the graph of the inverse voltage corrected for attenuation for each measurement frequency (figure II.10).



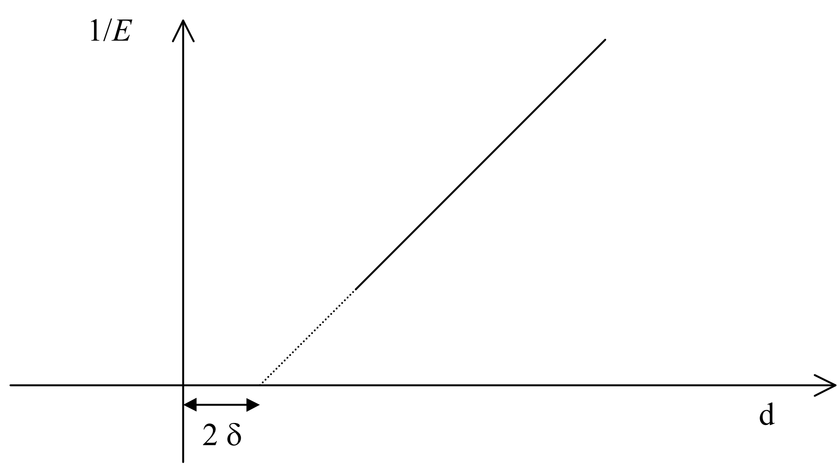


Figure II. 10: graph of the inverse voltage corrected for air attenuation as function of distance permitting determination of the acoustic center of the microphone.

II.7.5 Insert voltage technique

The free-field reciprocity calibration of microphones requires the measurement of the open-circuit voltage generated by the receiver microphone. Because of the high electrical impedance of the microphone, a special preamplifier that has high input impedance and low output impedance, is necessary to achieve this measurement.

In the insert-voltage technique [Hawley1949], first the microphone is exposed to the sound pressure P, which produces an open-circuit voltage E_0, and E at the preamplifier output. The sound pressure is then removed, and an insert voltage E_i is applied and adjusted until reaching the same voltage E at the preamplifier output. Thus, E_i is equal to the open-circuit voltage E_0 that the microphone generated when exposed to the sound.

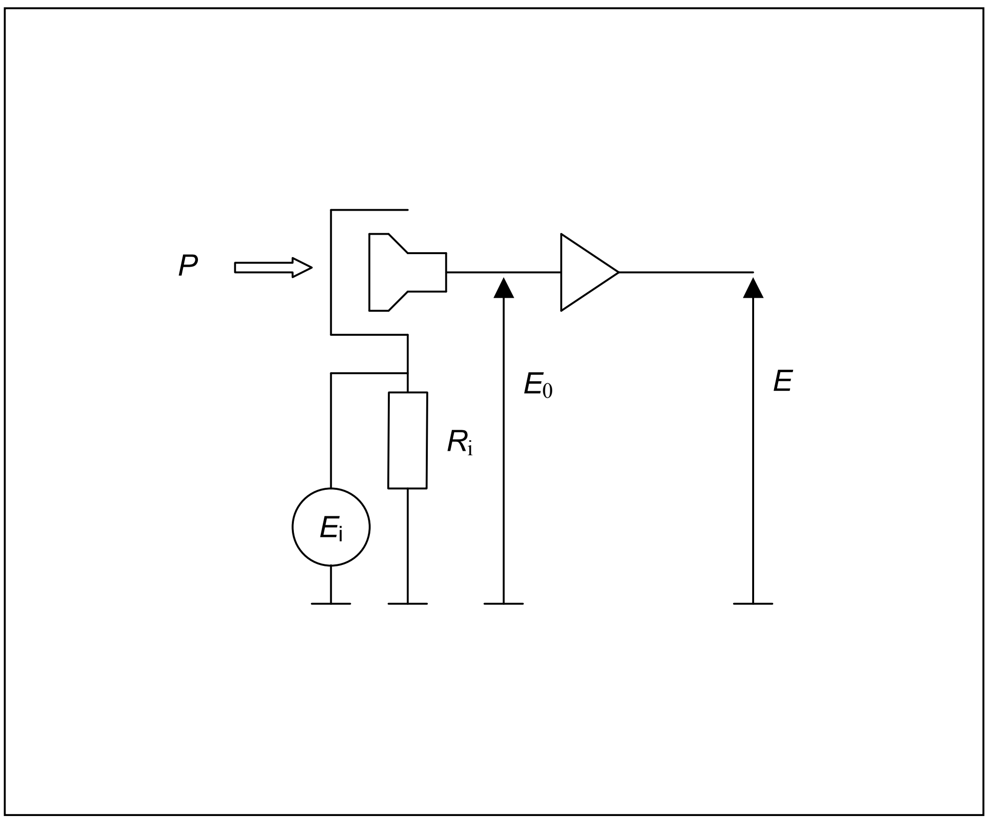


Figure II.11: The insert voltage technique.

II.7.6 Distortion of the driving voltage

Harmonic distortion in transducers is caused by the nonlinearity of the device, which is due to a combination of the transduction principle and the nonlinear effects of the material parameters.

The theory of reciprocity is based on the linearity of the condenser microphone, but in practice, when a microphone is acting as transmitter, for high driving voltages, the signal will be distorted due to its principle operation.

High voltages will result in distortion of the diaphragm movement generating harmonics noticeable at sub-multiples of the driving frequency. Therefore, the measured output at the fundamental frequency will be too low and, as a result, the calculated free-field sensitivity will be low as well.

In order to minimize the uncertainty due to distortion of the transmitter microphone, a small driving voltage relative to the polarizing voltage is required [Hunt1954], but in this case, the problem of poor signal-to-noise ratio will occur. A compromise should be made in the driving voltage value in order to get a good signal-to-noise ratio and a small distortion.

II.7.7 Effects of environmental conditions

The sensitivity of condenser microphone depends on the environmental conditions (static pressure, temperature and humidity) which affect the acoustic properties of the air behind the diaphragm. The measurement results should be corrected to the standard environmental conditions

$T = 23\ °\mathrm{C}$, $P = 101.325$ kPa and $H = 50$ %.

CHAPTER III

EXPERIMENTAL SET-UP AND MEASUREMENT RESULTS

III.1 Introduction

After describing the theory and practice of the free-field reciprocity calibration of condenser microphones, and discussing difficulties on confirming experimental conditions regarding the assumptions of the theory, in the previous chapter, this chapter is dedicated to the realization of a new experimental set-up for the free-field reciprocity calibration of ¼-inch microphones.
The reciprocity calibration of microphones requires three microphones; two of them must be reciprocal. This procedure is called the three-microphone method, or alternately, one can use two microphones: one of them must be reciprocal, and an auxiliary sound source, this is called the two-microphone method. The three-microphone method, which is more rigorous, is used in this calibration procedure. Three ¼-inch microphones B&K 4939 have been used because of their frequency range, which covers the low ultrasonic frequency-range, from 20 kHz to 160 kHz. Each microphone is used as a transmitter or receiver in three permutations, as shown in table III.1 and figure III.1

	Transmitter	Receiver
Combination a	Microphone 1	Microphone 2
Combination b	Microphone 2	Microphone 3
Combination c	Microphone 3	Microphone 1

Table III.1: The three pairs of microphone combinations.

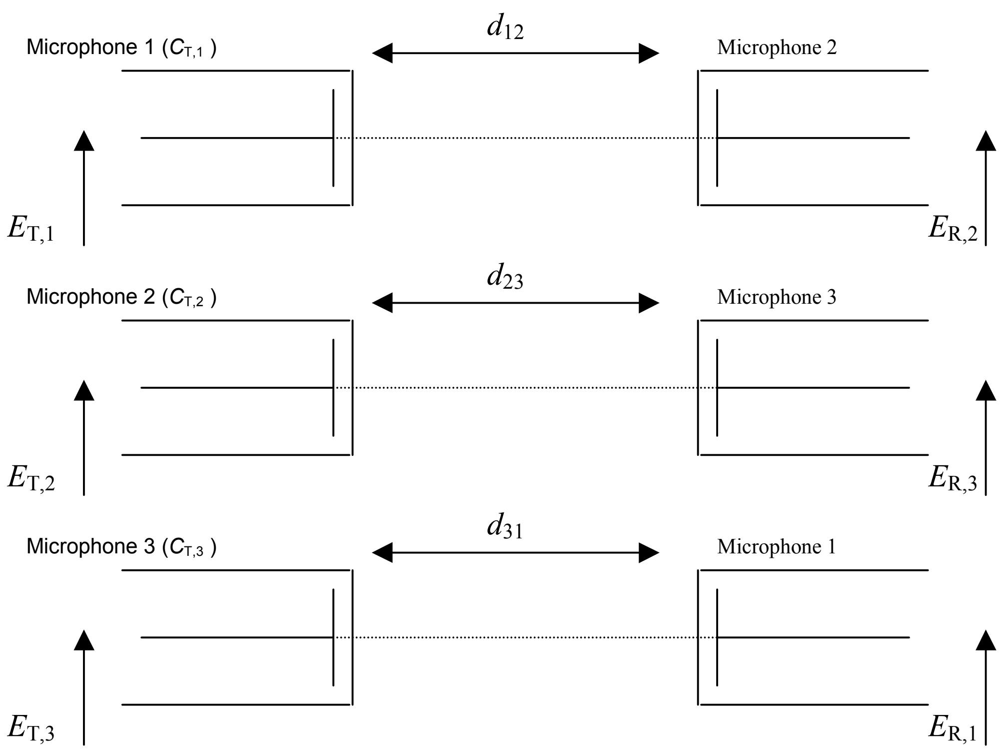


Figure III.1: Schematic diagram of the reciprocity calibration method for three microphones.

According to formula II.49 applied for the three combinations (a, b and c), three products of sensitivities M_1M_2, M_2M_3, M_3M_1 can be obtained. For example, the product of sensitivities M_1M_2 is given by:

$$M_1 M_2 = \left(\frac{E_{R,2}}{E_{T,1}} \cdot \frac{d_{12}}{\rho \cdot \pi \cdot f^2 \cdot C_{T,1}} \cdot e^{\alpha d_{12}} \right) \qquad \text{(III.1)}$$

The sensitivity of each microphone can then be deduced from the combination of the three products, e.g. the sensitivity M_1 can be obtained from:

$$M_1 = \left(M_1 \cdot M_2 \times M_2 \cdot M_3 / M_3 \cdot M_1 \right)^{1/2} \qquad \text{(III.2)}$$

where

$E_{T,1}$: Driving voltage of the transmitter microphone, microphone 1
$E_{R,2}$: Open-circuit voltage of the receiver microphone 2
$C_{T,1}$: Capacitance of the transmitter microphone, microphone 1
ρ: Density of air
f: Frequency
α: Attenuation of sound
d_{12}: Distance between acoustic centers of the microphones in the first combination

For the three combinations of microphones, the driving voltage of the transmitter microphone, the transmitter capacitance and the open-circuit voltage of the receiver microphone were measured within the frequency range from 20 kHz to 160 kHz (third-octave frequencies). The microphone capacitance was measured by a capacitance bridge of type 7600 Precision RLC Meter.
A new insert-voltage preamplifier was constructed for the calibration of ¼-inch condenser microphones, permitting measurement of the open circuit voltage of the receiver microphones by means of the insert voltage technique. A new measurement set-up was developed for the measurement of the open-circuit voltage of the receiver microphone.

This chapter describes the practical aspects and details of the measurement procedure and gives the measurement results.

III.2 Measurement procedure

Commercial insert-voltage preamplifiers are available only for 1-inch and ½-inch types of microphones [B&K1977]. A new insert-voltage preamplifier was constructed by Microtech Gefel (a German company) according to our specifications specially for the present measurement set-up, the insert-voltage preamplifier is mounted on a tubular rod having the diameter of a ¼-inch microphone (figure III.1-a).
A SOLARTRON 1255 Frequency Response Analyzer was used as a generator and analyzer. A polarizing voltage of 200 V was applied to the transmitter microphone through a resistor of 100 MΩ. A constant alternating voltage was applied through a 200 pF capacitor to excite the transmitter microphone.

The open-circuit voltage on the receiver E_r is measured by means of the insert-voltage technique.
For each frequency, two measurements are performed: first the gain for the receiving part of the set-up (figure III.4), and second the output voltage of the receiving microphone.

First, switch 1 is in the position A, the amplification of the receiving part of the set-up is determined by the difference between the measured voltage E_1 and the insert voltage E_0.

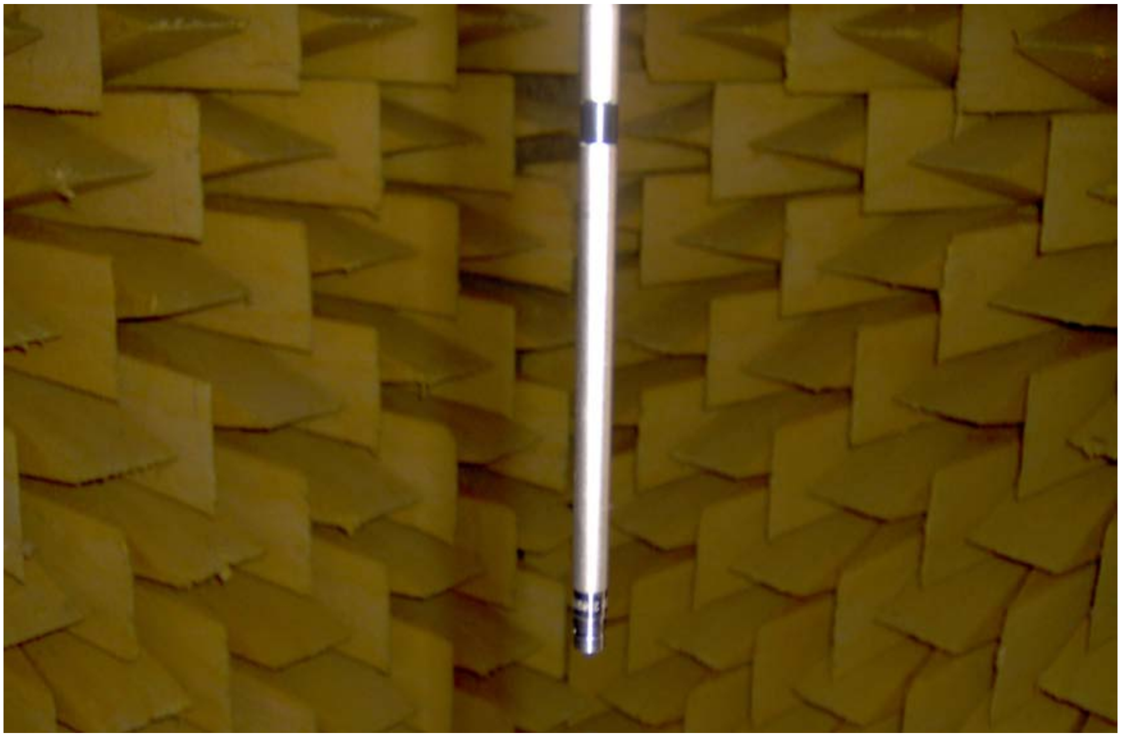
$$G = E_1 - E_0 \qquad \text{(III.3)}$$

In the second measurement, switch 1 is in the position B and the transmitter microphone is excited by a constant alternating voltage. The open-circuit voltage of the receiver microphone is determined by calculating the difference between the output voltage E_r measured at the input 1 of the SOLARTRON and the gain of the amplification stage of the receiving part G given by the first measurement.
The measurements are performed at a number of microphone separations for all frequencies. The distance range is 100 mm to 300 mm.
In the free-reciprocity calibration, the measurement accuracy of the receiver microphone E_r can be affected by:

- the performance of the anechoic room in the ultrasonic frequency range;
- the acoustic and electric noise;
- cross talk;
- standing waves and reflections;
- the distortion of the output signal;
- the acoustic center and measurement distance; and
- the correction for environmental conditions

All these parameters are optimized during the realization of the measurement set-up and the calculation procedure of the free-field sensitivity.

a)



b)

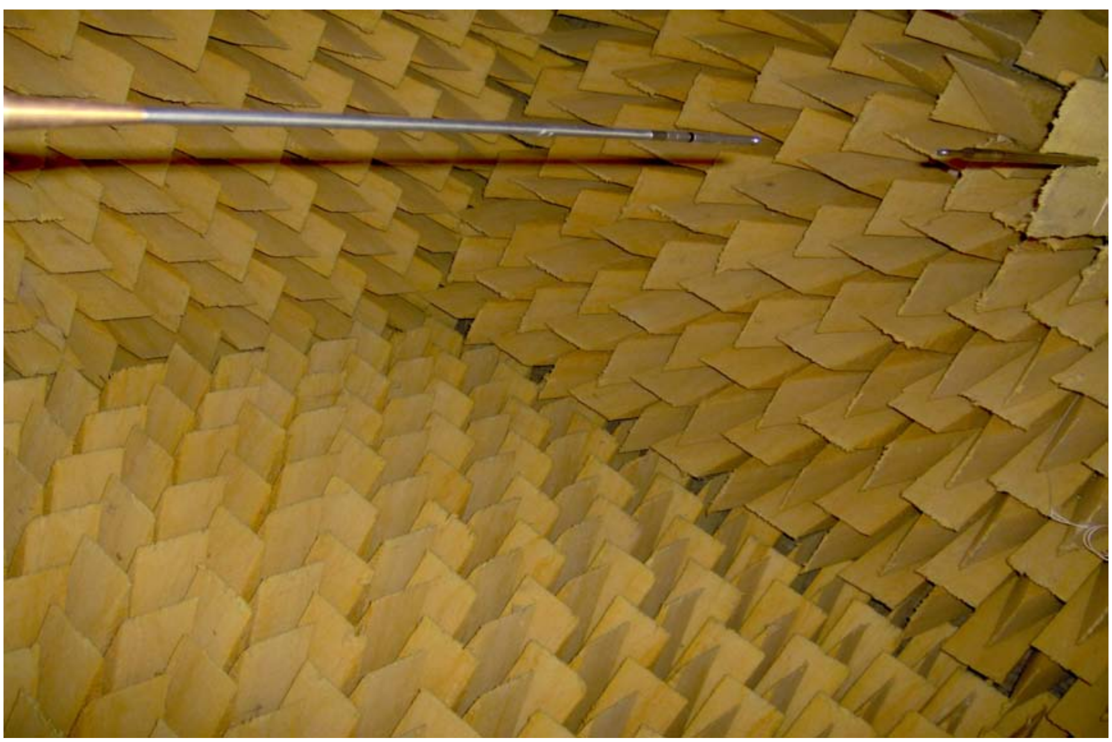


Figure III.2: Photos of the measurement set-up: a) Receiver microphone and the preamplifier inside the anechoic chamber, b) transmitter and receiver microphones mounted inside the anechoic chamber

a)

b)

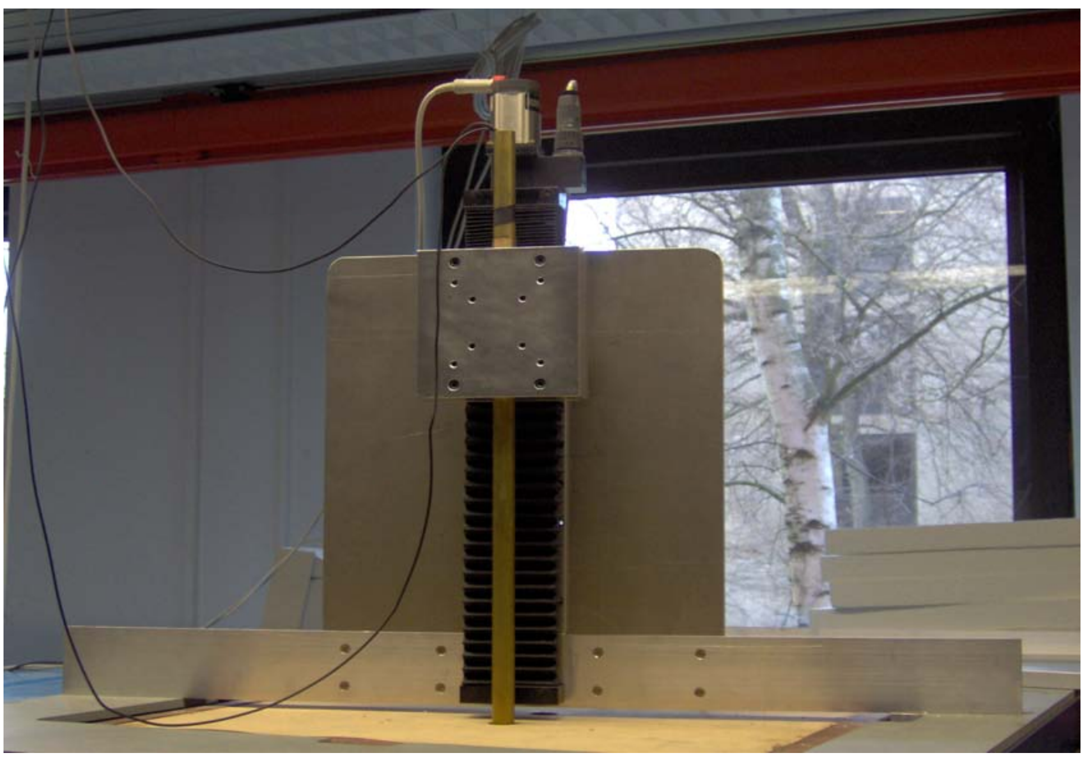


Figure III.3: Photos of the measurement set-up: a) equipment used in the measurements, b) stepping motor used for the control of the distance between the two microphones.

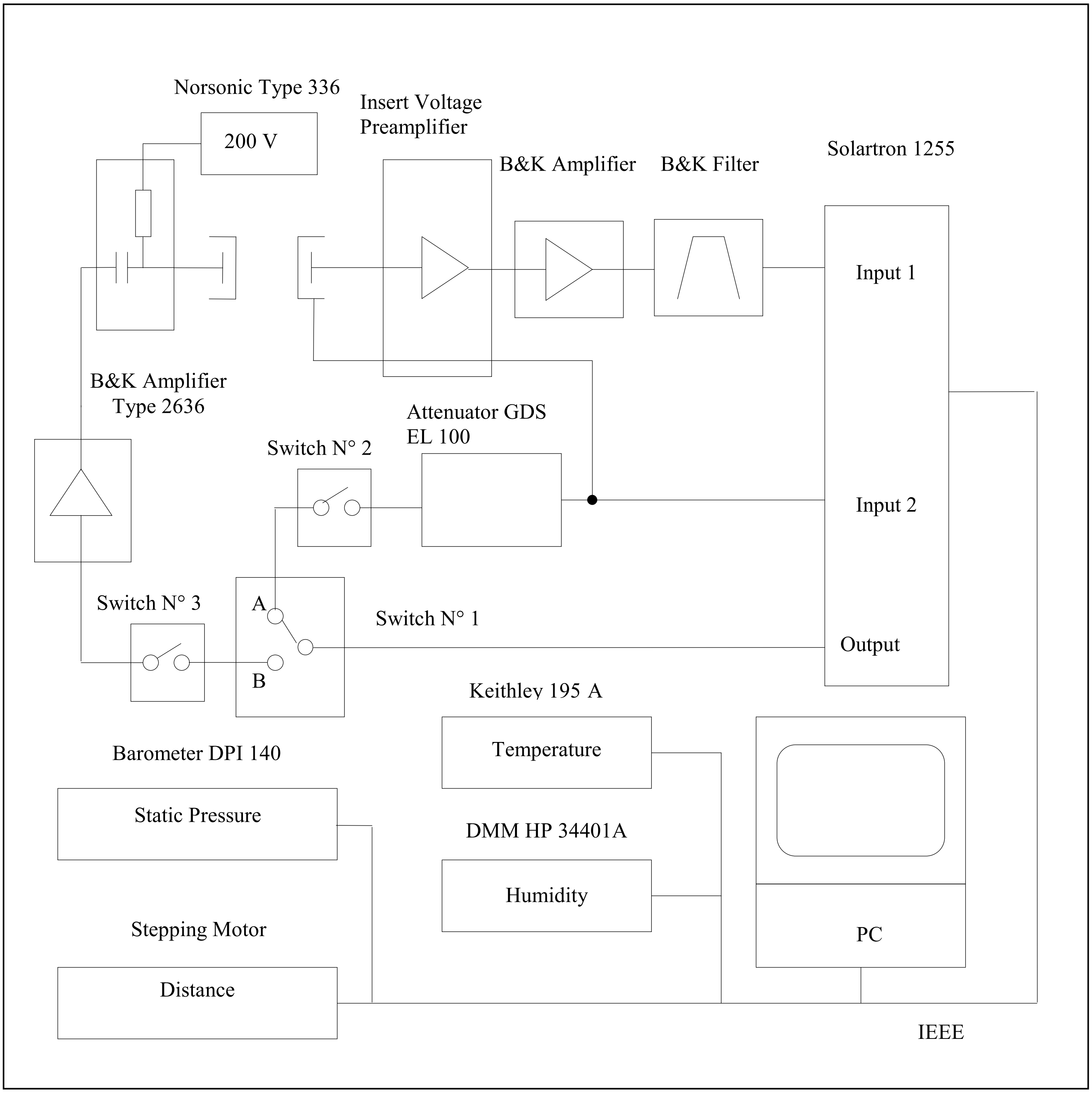


Figure III.4: Schematic diagram of the measurement set-up for free-field reciprocity calibration of ¼-inch condenser microphones.

III.3 Performance of the anechoic room for ultrasonic frequencies

The first requirement for free-field measurement is an anechoic chamber. Figure III.5 shows the chamber used for the present measurements, a cabinet of 15 m^3 net volume, installed in an audiometric container shielded against electromagnetic interferences. All sides of the chamber are clad with glass fiber wedges having a base of 80 mm by 80 mm and a length of 350 mm (figure III.5). The length and width between the tips of the wedges is 2 m, the height is 3.7 m. For all calibrations, the transmitter microphone is located at 700 mm above the wedges of the floor. The transmitter rod is a cylinder of ½-inch diameter with a length of 640 mm curved to ¼-inch diameter with a length of 60 mm, whereas, the receiver microphone is positioned by its long support tube into an arbitrary position, in axis with the direction of the transmitter microphone. The support tube consists of three cylinders of diameter 1-inch, ½-inch and ¼-inch respectively with a length of 2000 mm, 1000 mm and 400 mm (figure III.5).

The positioning system is realized by means of a stepping motor (figure III.3-b), which has a working range of 300 mm. For each measurement, an initial setting of the positioning system is done by means of a digital calliper.

The free-field performance of this anechoic room in the audio frequency range was proven in an earlier work [Obermayr1992a] [Obermayr1992b]. Prior to this work, no measurement had been done in this anechoic room in the ultrasonic frequency range above 40 kHz. In a free field, the sound pressure is proportional to the inverse of the distance from the acoustic center of the source, which is called "inverse distance law". By measuring the deviation from the ideal behavior of the measured variation of the sound pressure with distance from the acoustic center of the source, the performance of the anechoic room can be assessed [Delany1977] [Ballagh1985]. [Bay2005]

The sound pressure was measured at a fixed position as the receiver microphone was traversed away in uniform steps.
Measurement results for frequencies from 20 kHz to 160 kHz, for a distance from 100 mm to 300 mm, are shown in figure III.6a-e.

The deviation in the measurement results from the inverse distance law (6 dB for the double distance) can be attributed to acoustic or electrical sources of error. The acoustic sources of error are due to acoustic noise and to interference phenomena arising from the reflection from the walls of the anechoic room, reflection and diffraction from the supporting rod of the microphones, and standing waves between transmitter and receiver microphones. The electrical sources of error are due to electrical noise and electrical interferences between the transmitter and receiver microphones (crosstalk).

During the first measurements, the results were affected by an important sinusoidal disturbance, having the same wavelength as the driving signal, for each measurement frequency. Great effort has been done to identify the cause of this disturbance and therefore to eliminate it, as far as possible. This disturbance was particularly strong at lower frequencies, where the signal is low, and it was observed that it increases with distance, where the signal is low, as well. Particular attention was given to the crosstalk in the output signal of the receiver microphone, which could lead to such results. Several steps were taken to minimize the level of crosstalk; they will be discussed in paragraph III.5.

A second type of sinusoidal disturbance was observed, having a half wavelength of the driving signal at higher frequencies more than 80 kHz. It was observed that this effect decreases with distance. The origin of this disturbance is the standing waves between transmitter and receiver microphones.

a)

b)

c)

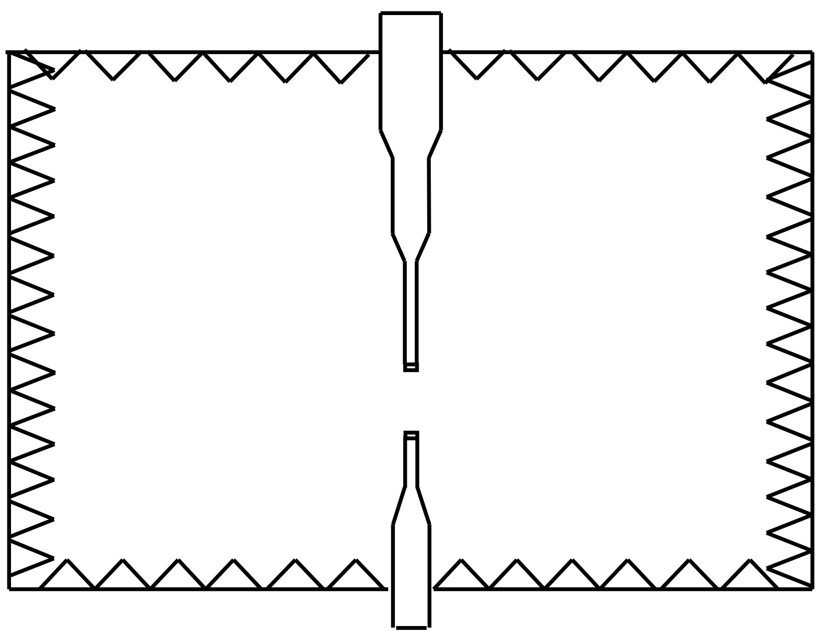


Figure III.5: a) Anechoic chamber of measurement. b) Wedge of the anechoic chamber. c) Schematic diagram of the transmitter and receiver microphone mounted inside the anechoic chamber

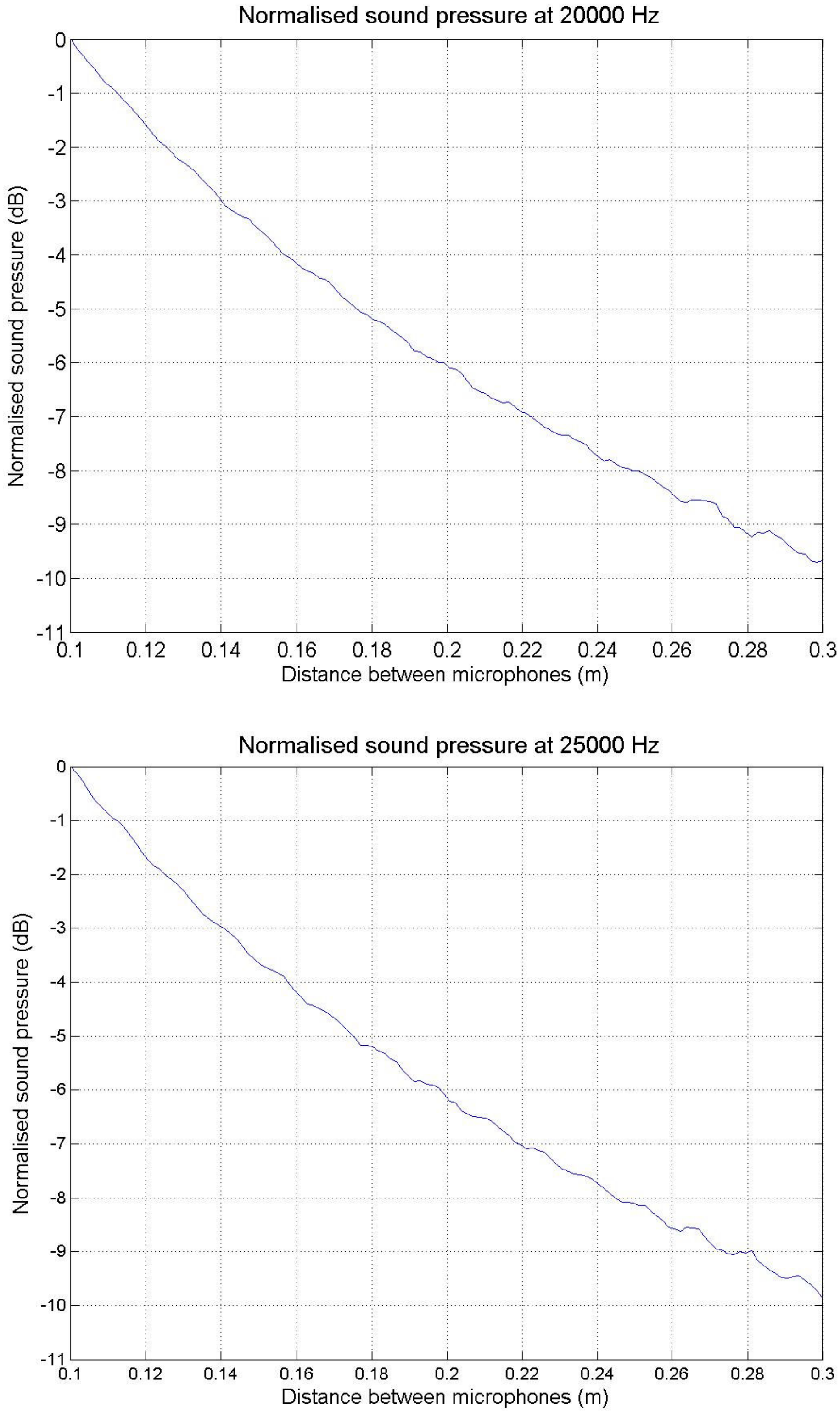
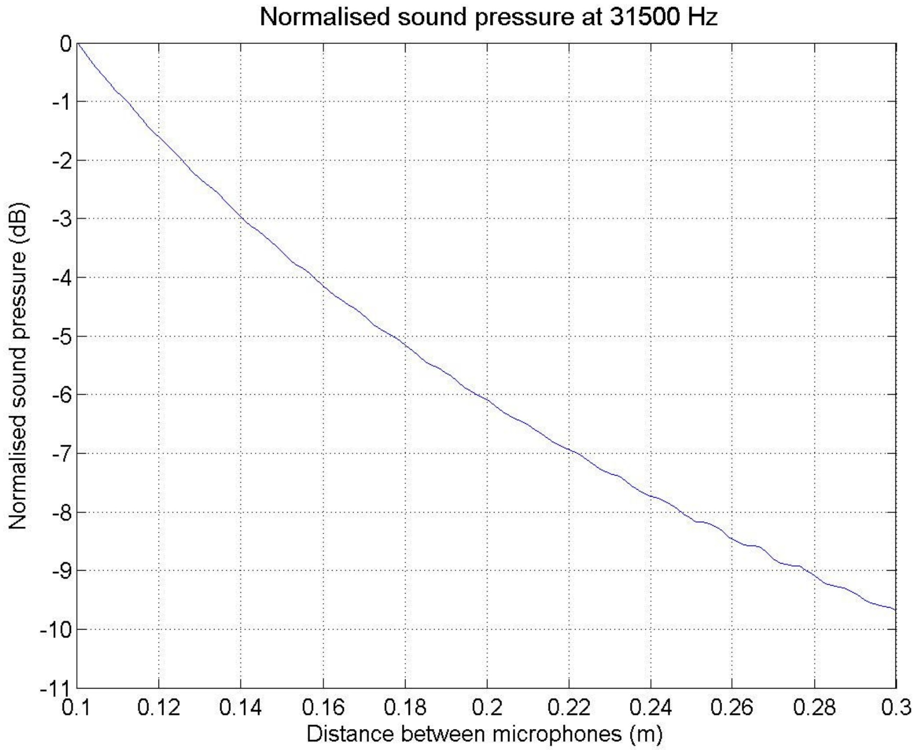


Figure III.6-a: Free-field performance of the anechoic room, at 20 and 25 kHz.



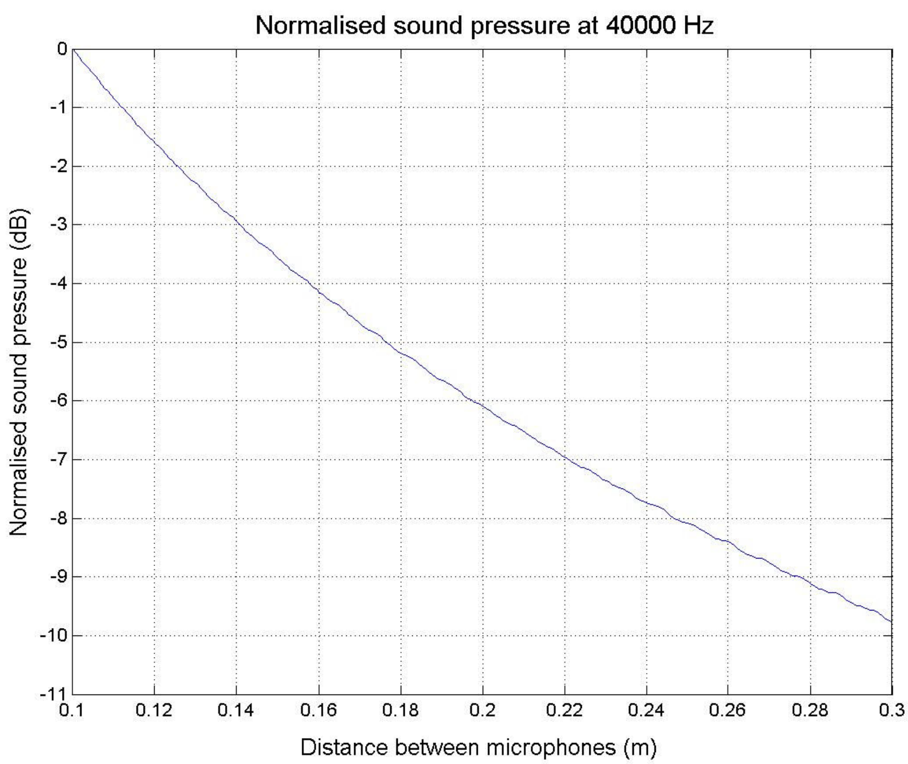
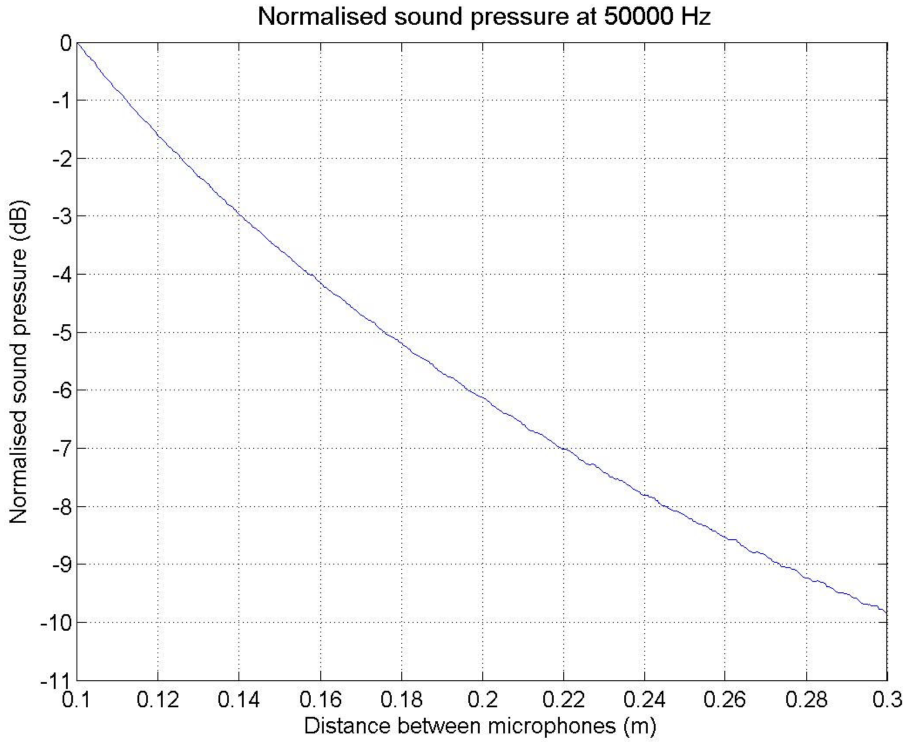


Figure III.6-b: Free-field performance of the anechoic room, at 31.5 and 40 kHz.



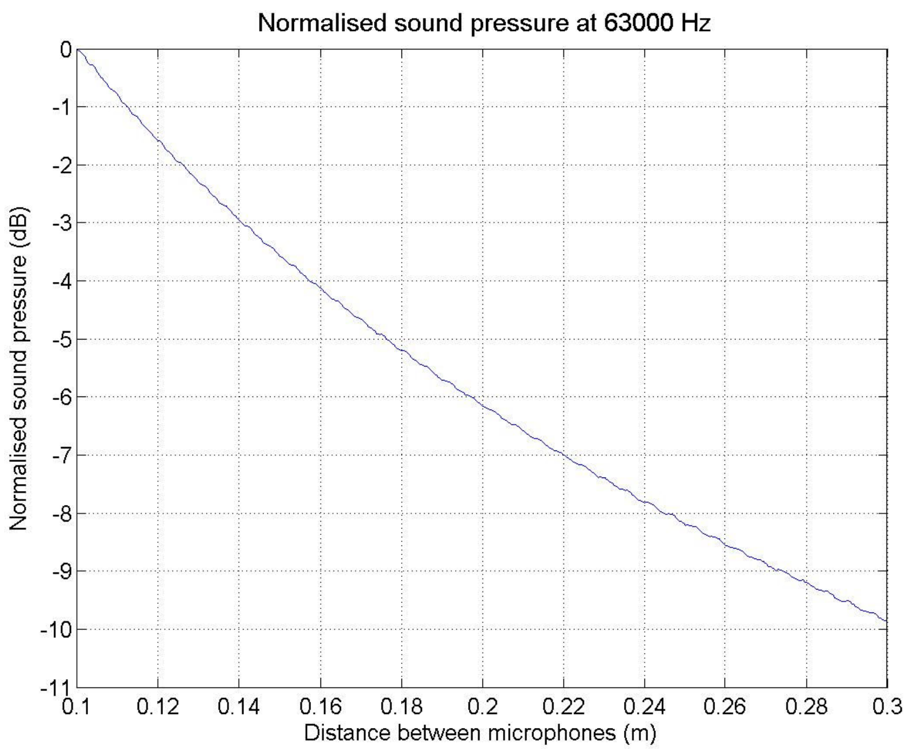


Figure III.6-c: Free-field performance of the anechoic room, at 50 and 63 kHz.

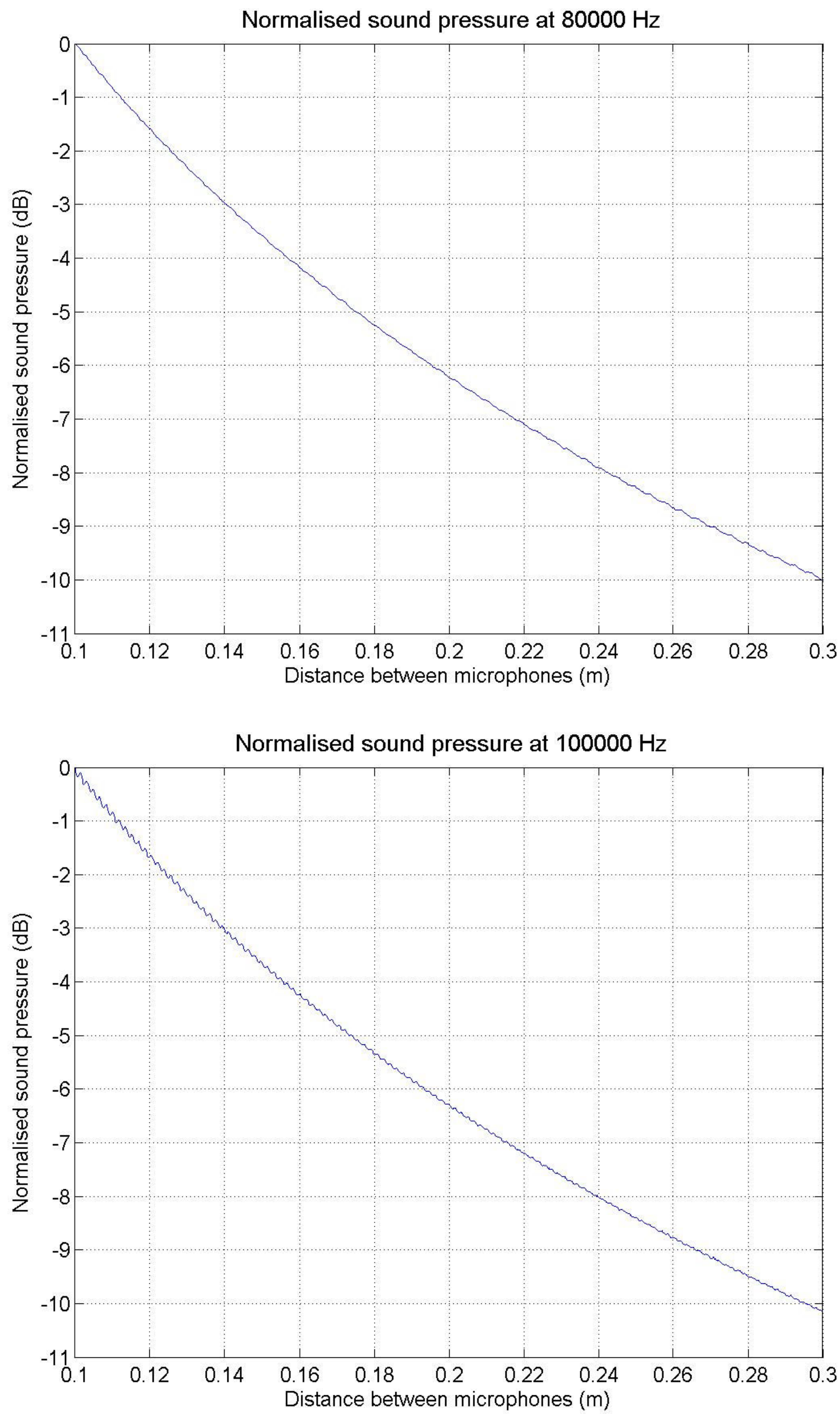
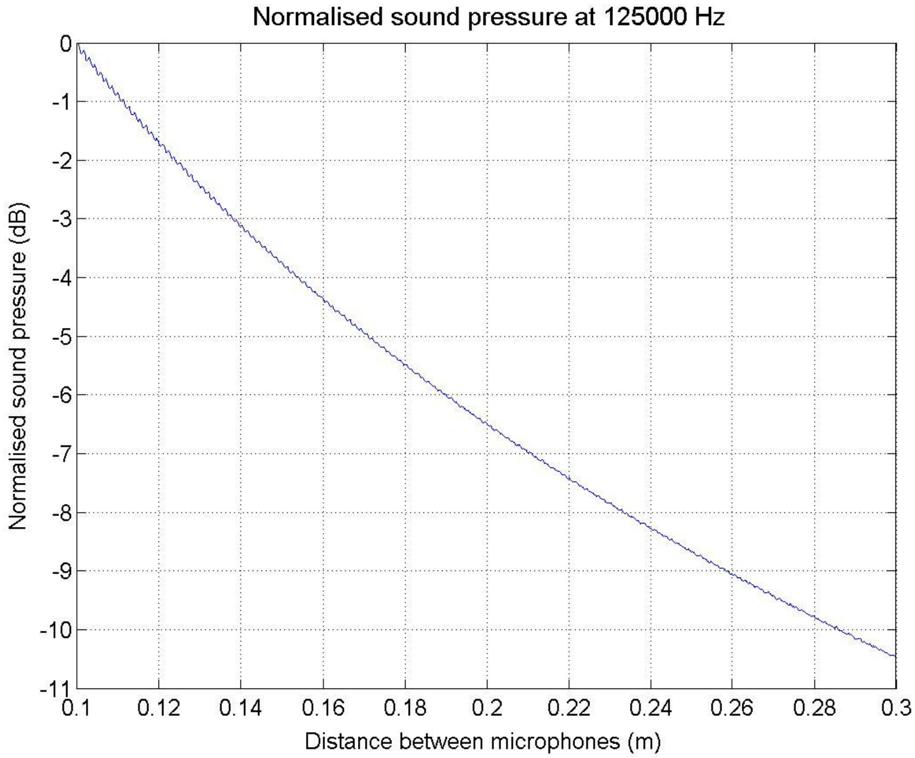


Figure III.6-d: Free-field performance of the anechoic room, at 80 and 100 kHz.



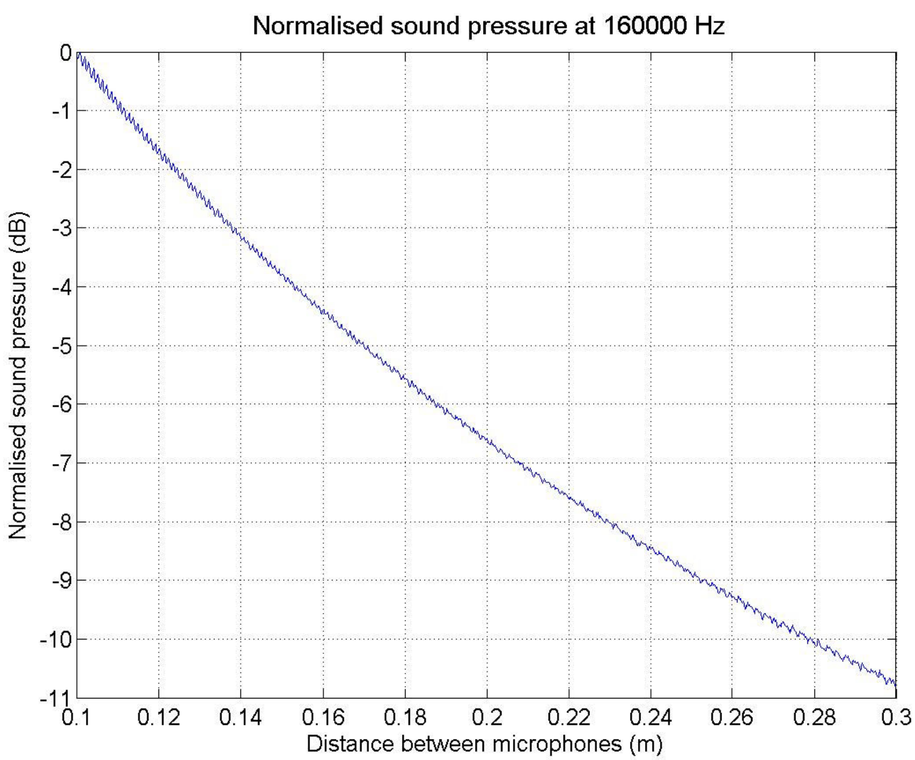


Figure III.6-e: Free-field performance of the anechoic room, at 125 and 160 kHz.

III.4 Effects of noise

The sound pressure level to be measured with the receiver microphone is too low, at lower frequencies. Consequently, to make a precise measurement during the free-field reciprocity calibration of microphones, a good isolation of the anechoic room from external noise is necessary. A narrow-bandwidth filter helped to achieve a sufficient precision.

The signal-to-noise ratio whether of electrical or acoustical in origin was also improved at low frequencies by a sufficiently high integration time of the frequency response analyzer SOLARTRON.
The open-circuit voltage of the receiver microphone is proportional to the square of the frequency, thus, at lower frequencies, where the receiver voltage is low, the integration time of the SOLARTRON is 25 s. The integration time decreases to 1s at 80 kHz.
Figure III.7 shows the signal-to-noise ratio measured for 3 V driving voltage of the transmitter microphone with a distance of 200 mm between transmitter and receiver microphones. The signal-to-noise ratio exceeds 50 dB, so the systematic error in the measured voltage is therefore lower than 0.0001 dB.

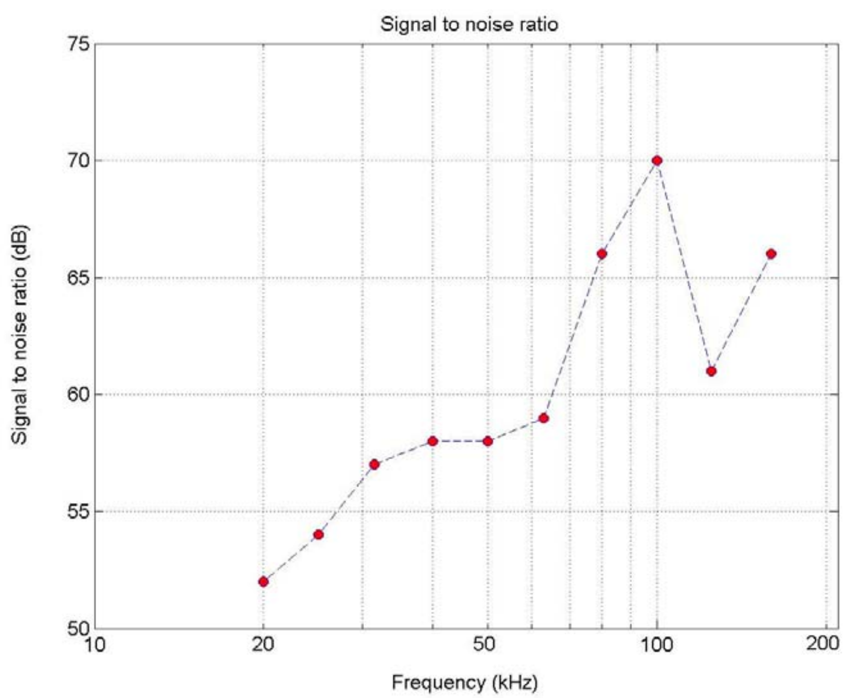


Figure III.7: Signal-to- noise ratio for a distance of 200 mm and a driving voltage of 3 V.

III.5 Effects of crosstalk and standing waves

During the development of the measurement set-up for the free-field reciprocity calibration of condenser microphones, one of the major practical problems to be solved was crosstalk because of the low output voltage of the receiver microphone. When 3 V drive the transmitter microphone, the open-circuit voltage of the receiver microphone is in the order of μV, such a difference in voltage levels between the transmitter and the receiver microphones leads to electrical crosstalk problems.

The identification and the evaluation of the level of crosstalk were performed in two ways: a stepping motor, allowing the scanning of the acoustic field as function of the distance, and the test of the deviation from the inverse distance law; by means of a measuring capacitance used as a transmitter, permitting a direct evaluation of the crosstalk.

The automatic positioning system (stepping motor) allows scanning of the acoustic field by measuring the output voltage of the receiver microphone as a function of the distance, for small intervals of microphone separation. A good resolution of the distance interval is needed at higher frequencies where the wavelength of the signal is small, so the number of distance intervals must be high in order to detect the sinusoidal disturbance of crosstalk (one wavelength periodicity). The second means of detecting crosstalk is to replace the transmitter microphone by a measuring capacitance having the same capacitance as the transmitter microphone, so that there is no acoustical signal and the measured electrical signal at the receiver microphone is the level of crosstalk.

For the optimization of the measurement set-up, several steps were taken progressively to minimize and control the level of crosstalk. Separation between high-level and low-level parts of the circuit: the cable driving the signal to the transmitter microphone, and the cable coming from the receiver microphone were separated by a few meters. One other principal problem, which increases crosstalk, was the grounding of the system. The circuit of measurement was analyzed, and some ground loops were identified and eliminated. Another parameter for the reduction of the crosstalk was the use of an optical interface for the computer control of the instrumentation.

Figure III.8 shows the measured signal-to-crosstalk ratio as function of frequency, for a distance of 200 mm, which is greater than 38 dB for frequencies from 20 kHz to 160 kHz. Thus, the uncertainty due to crosstalk will be less than 0.1 dB.

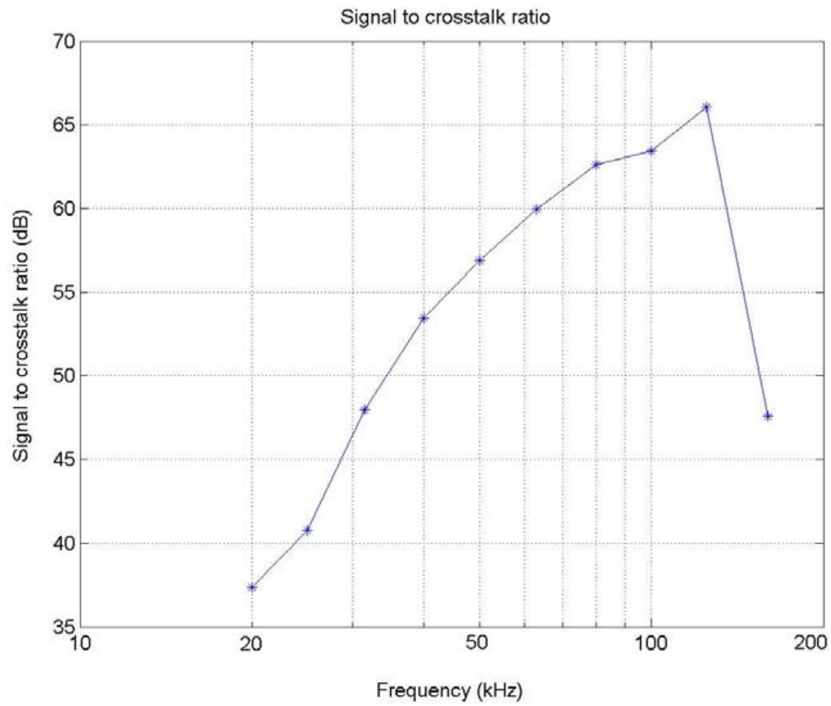


Figure III.8: Signal to crosstalk ratio at distance of 200 mm.

To evaluate the effects of crosstalk and standing waves, the deviations from the inverse distance law have been examined. As described in chapter II, standing waves due to reflections between the transmitter and receiver microphones will produce sinusoidal interferences with a periodicity of half a wavelength in distance. Such phenomena are seen at higher frequencies where the diameter of the microphone is much larger compared to the acoustic wavelength, so the microphone can be assimilated to a big reflector; this effect is less pronounced as the distance between the microphones increased. However, crosstalk will produce sinusoidal interferences with a periodicity of one wavelength in distance. Such phenomena are seen at lower frequencies where the voltage of the receiver microphone is low; this effect is more pronounced with increasing distance.

In order to minimize the uncertainty due to crosstalk and standing waves, a distance range from 100 mm to 200 mm is chosen (signal-to-crosstalk ratio decreases with increasing distance), below 40 kHz. At higher frequencies (above 80 kHz), the effects of standing waves become dominant, therefore a larger distance range (200 mm to 300 mm) is used for measurements to minimize these effects. In the middle frequencies, between 40 kHz and 80 kHz, a distance range (150 mm to 250 mm) is used.

The measurement results of are shown in figures III.9a-j. The open-circuit voltage of the receiver microphone is measured as function of distance and frequency (first graph) and then corrected for the air attenuation and inverted (graph below). The deviation is then deduced from the difference between these data and the inverse distance law for each frequency as function of distance (graph below).

For a simple explanation of the effects of crosstalk and standing waves, the spectrum of these deviations is shown for each frequency. The spectrum of these deviations was obtained by multiplying the distance unit by the sound velocity (345 m/s) to obtain the time unit, and then applying the Fast Fourier Transform (FFT) to the deviation signal from the inverse distance law (graph below).

As can be seen in figures III.9a-j, below 80 kHz, the deviation contains one component (one wavelength), the spectrum contains one peak at the frequency of measurement (one-wavelength component), and the deviation is therefore due to crosstalk. For frequencies above 80 kHz, the effect of standing waves becomes more pronounced, so that the deviation contains two components (one wavelength and half a wavelength), the spectrum contains two peaks; one at the frequency of measurement (one-wavelength component) is due to crosstalk. The second peak at two times of the measurement frequency (component half-wavelength) is due to standing waves.

The deviation from the inverse distance law (due to crosstalk and standing waves) is less than 1.2 % (0.1 dB) for the frequency range from 20 kHz to 160 kHz.

a)
b)
c)
d)

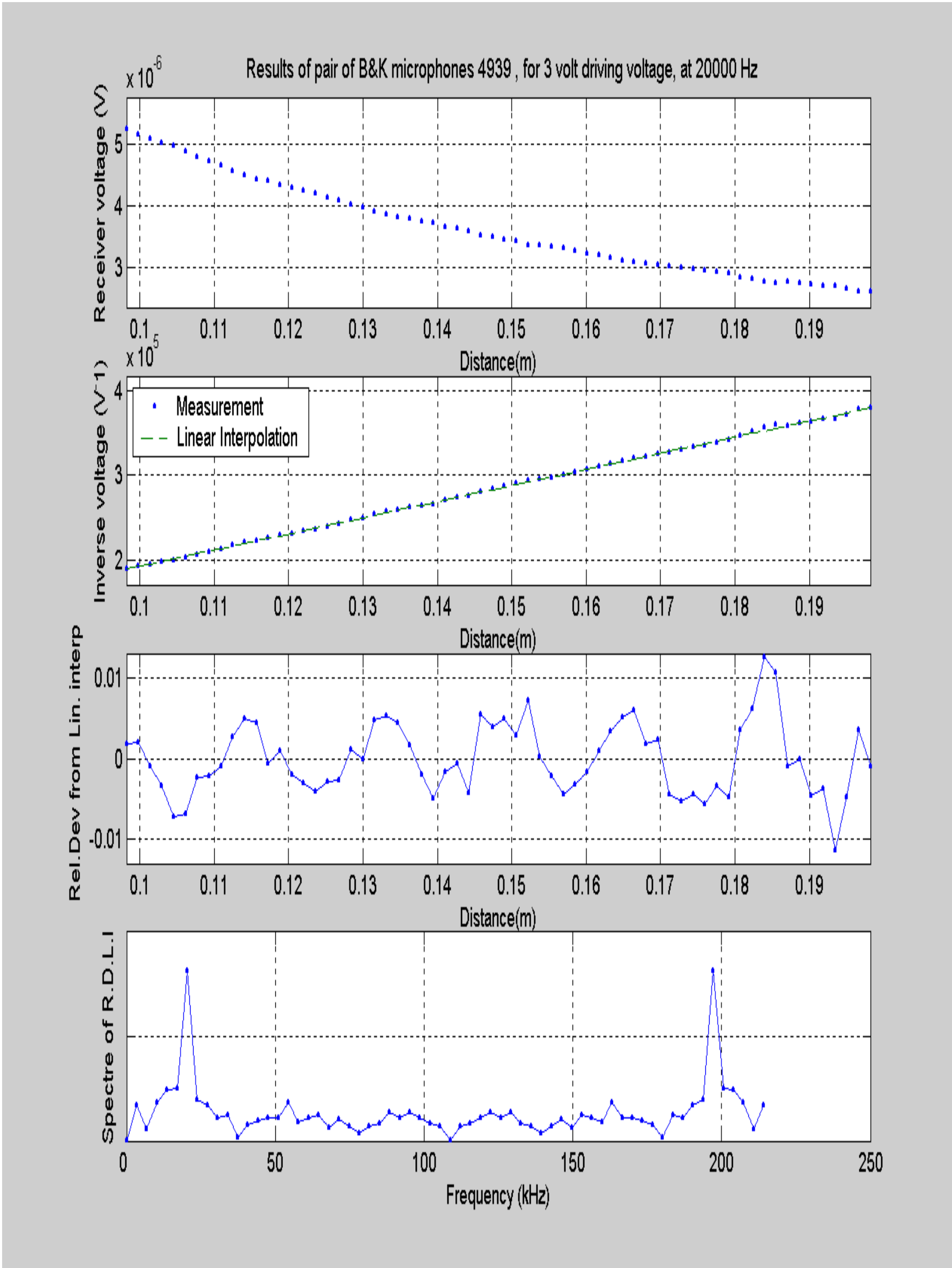


Figure III.9-a: Measurement results for microphones B&K 4939 at 20 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 1.2%. d) Spectrum of the deviations of the measured data from the inverse distance law.

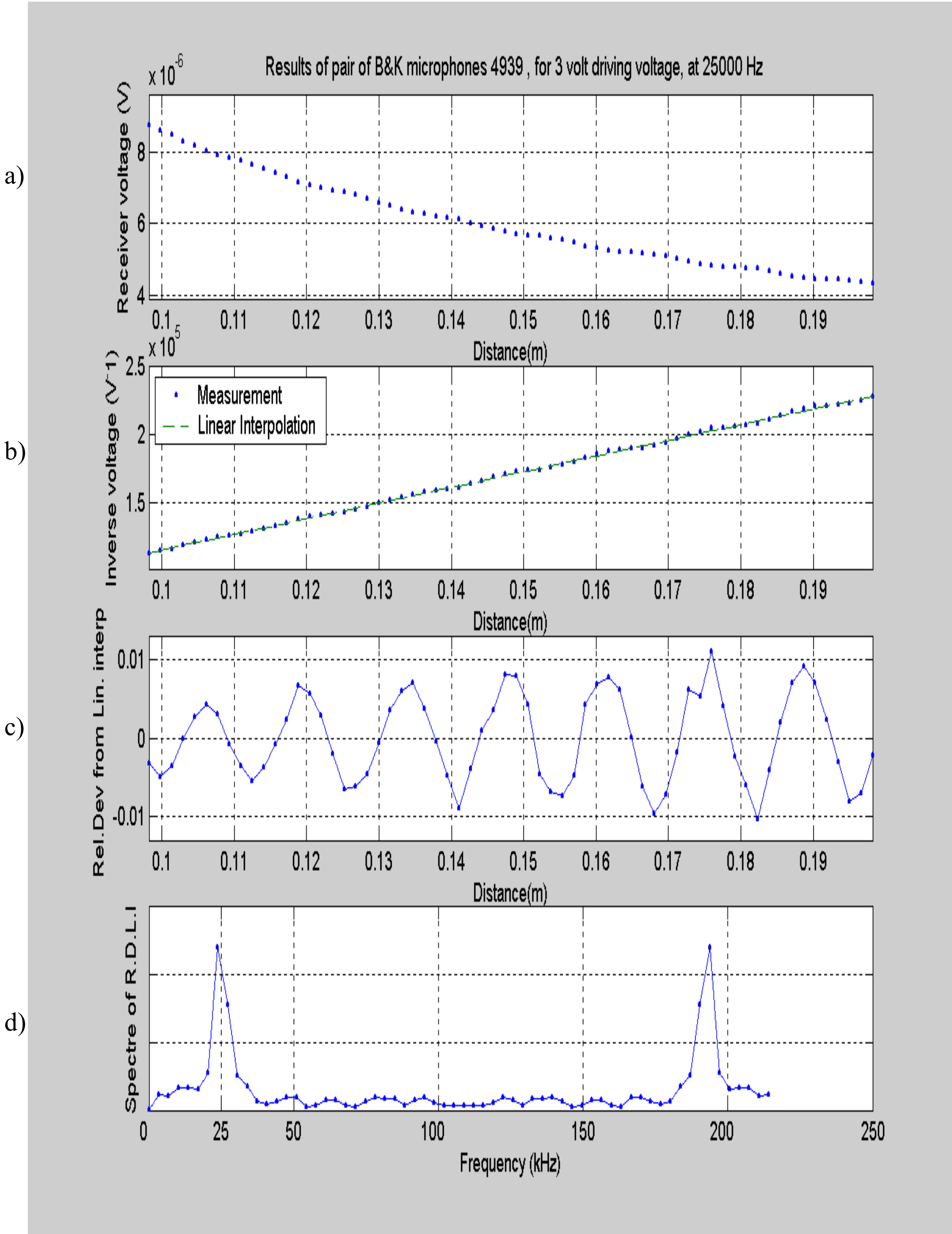


Figure III.9-b Measurement results for microphones B&K 4939 at 25 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 1.1%. d) Spectrum of the deviations of the measured data from the inverse distance law.

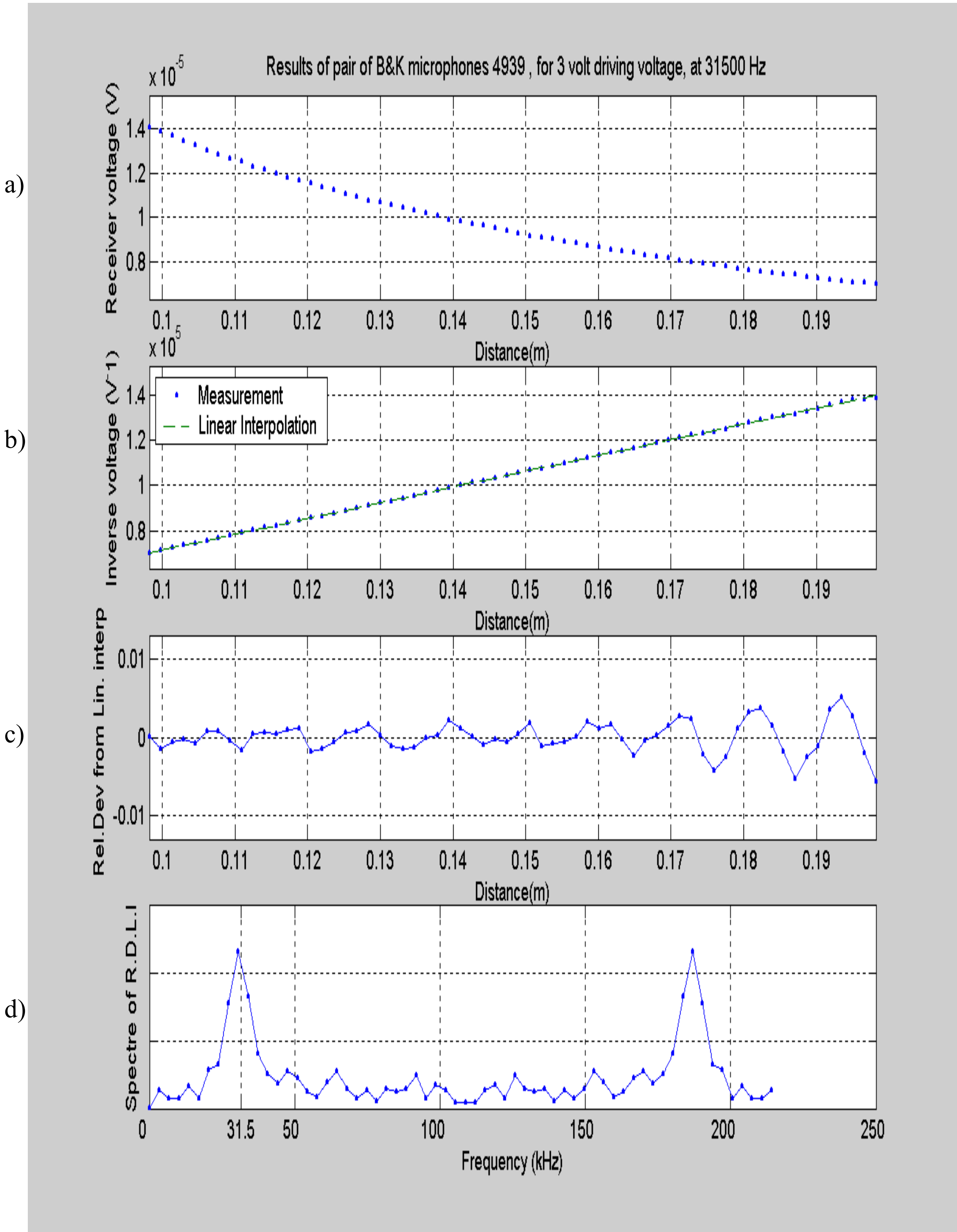


Figure III.9-c: Measurement results for microphones B&K 4939 at 31.5 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.5%. d) Spectrum of the deviations of the measured data from the inverse distance law.

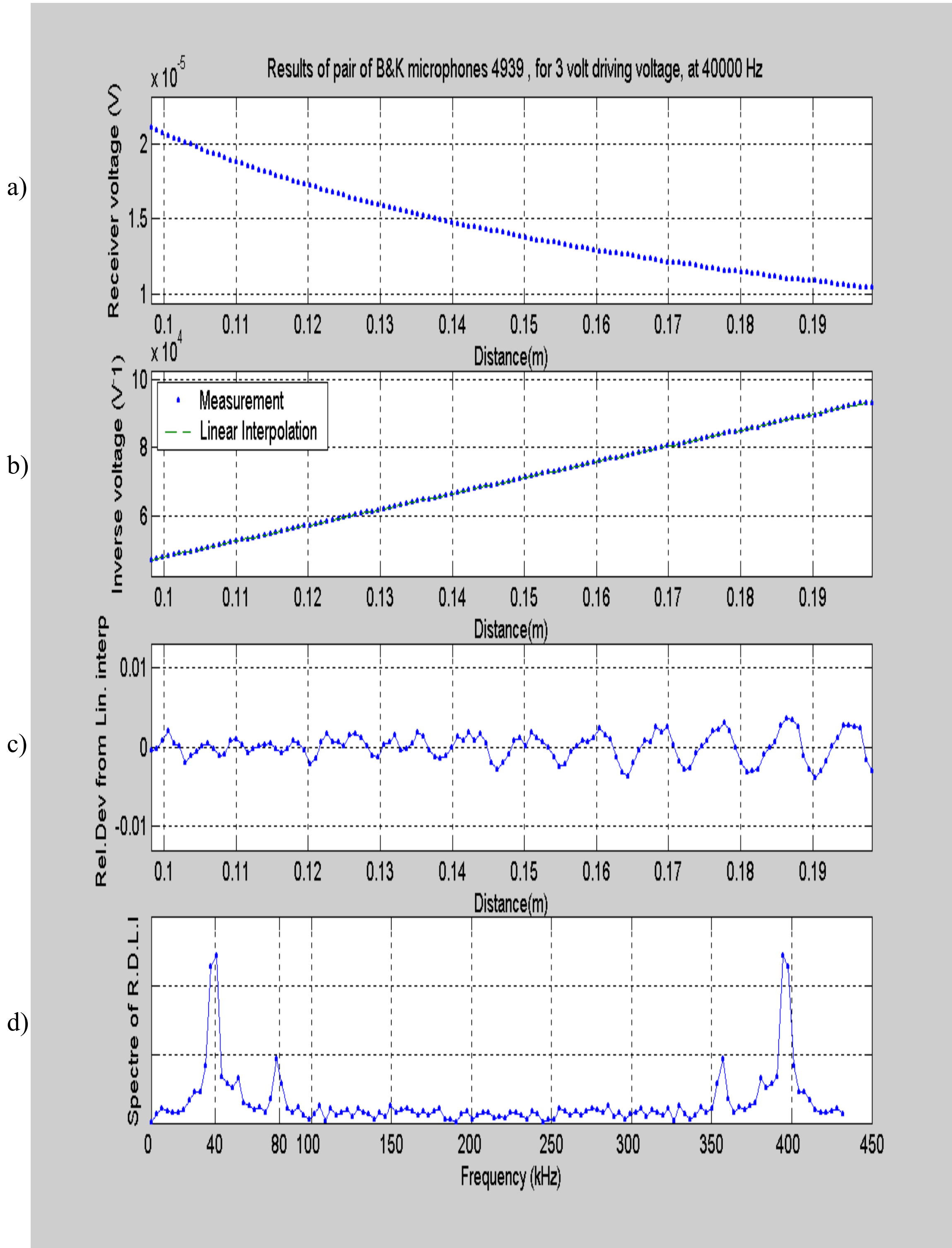


Figure III.9-d: Measurement results for microphones B&K 4939 at 40 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.4%. d) Spectrum of the deviations of the measured data from the inverse distance law.

a)

b)

c)

d)

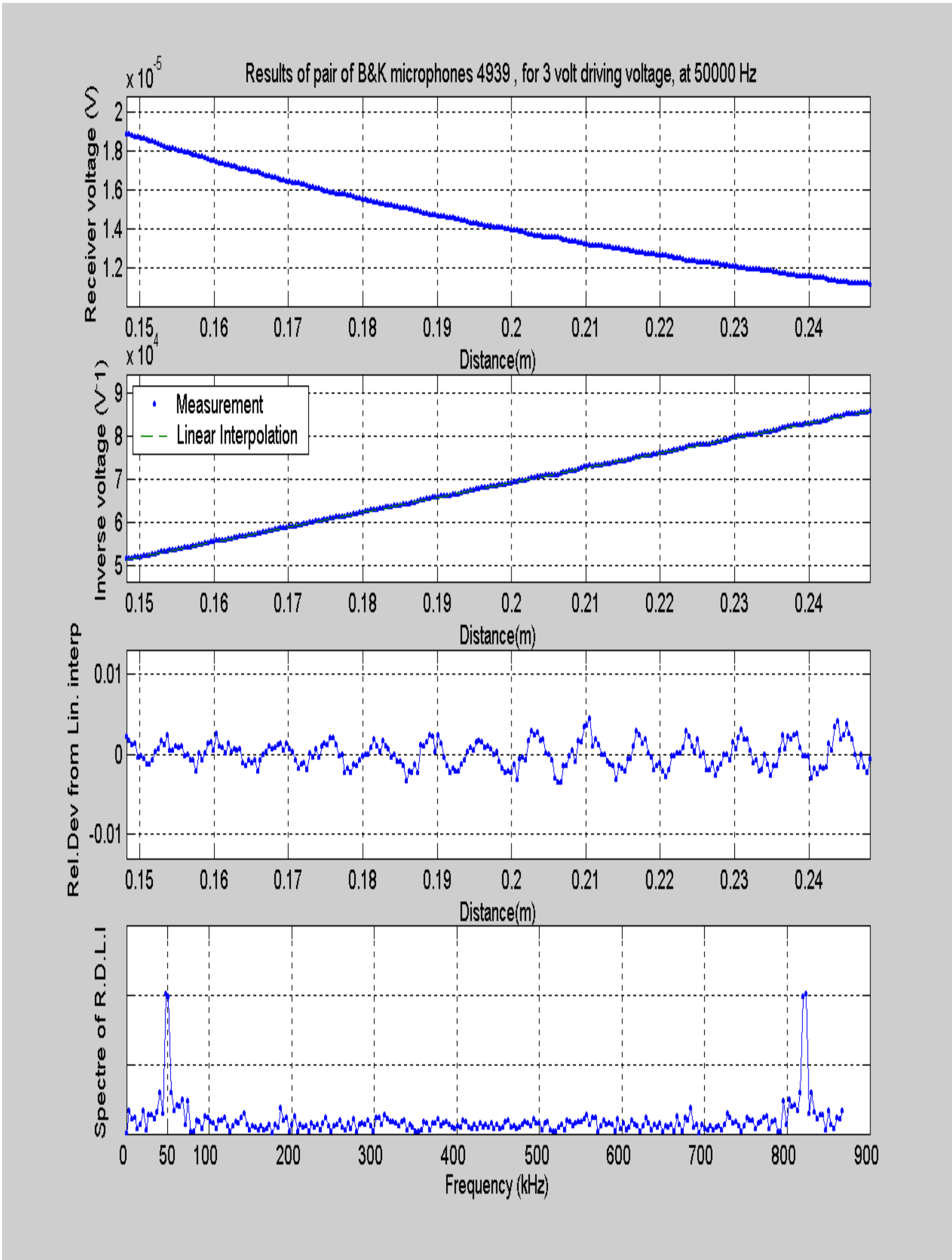


Figure III.9-e: Measurement results for microphones B&K 4939 at 50 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.43%. d) Spectrum of the deviations of the measured data from the inverse distance law.

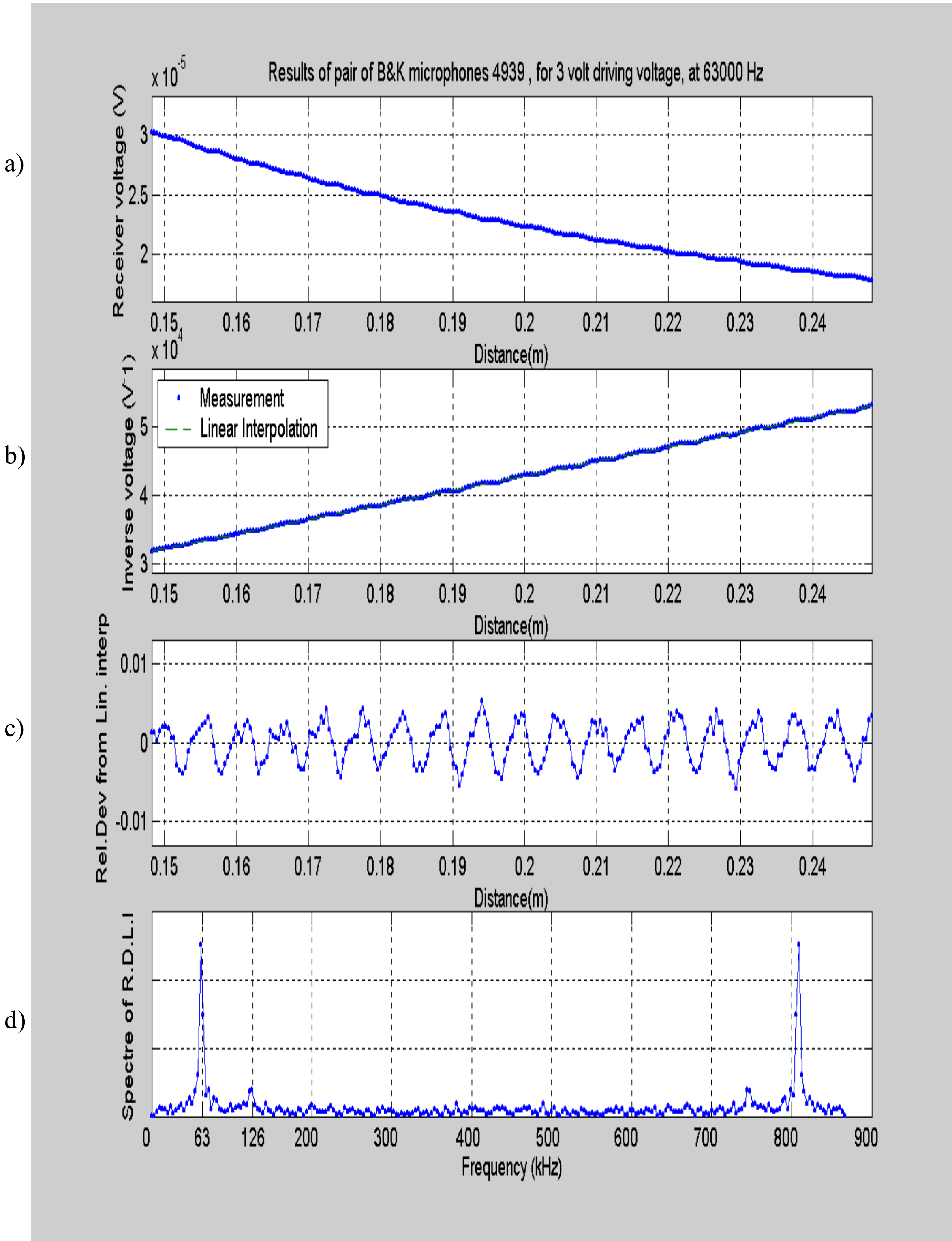


Figure III.9-f: Measurement results for microphones B&K 4939 at 63 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.53%. d) Spectrum of the deviations of the measured data from the inverse distance law.

a)
b)
c)
d)

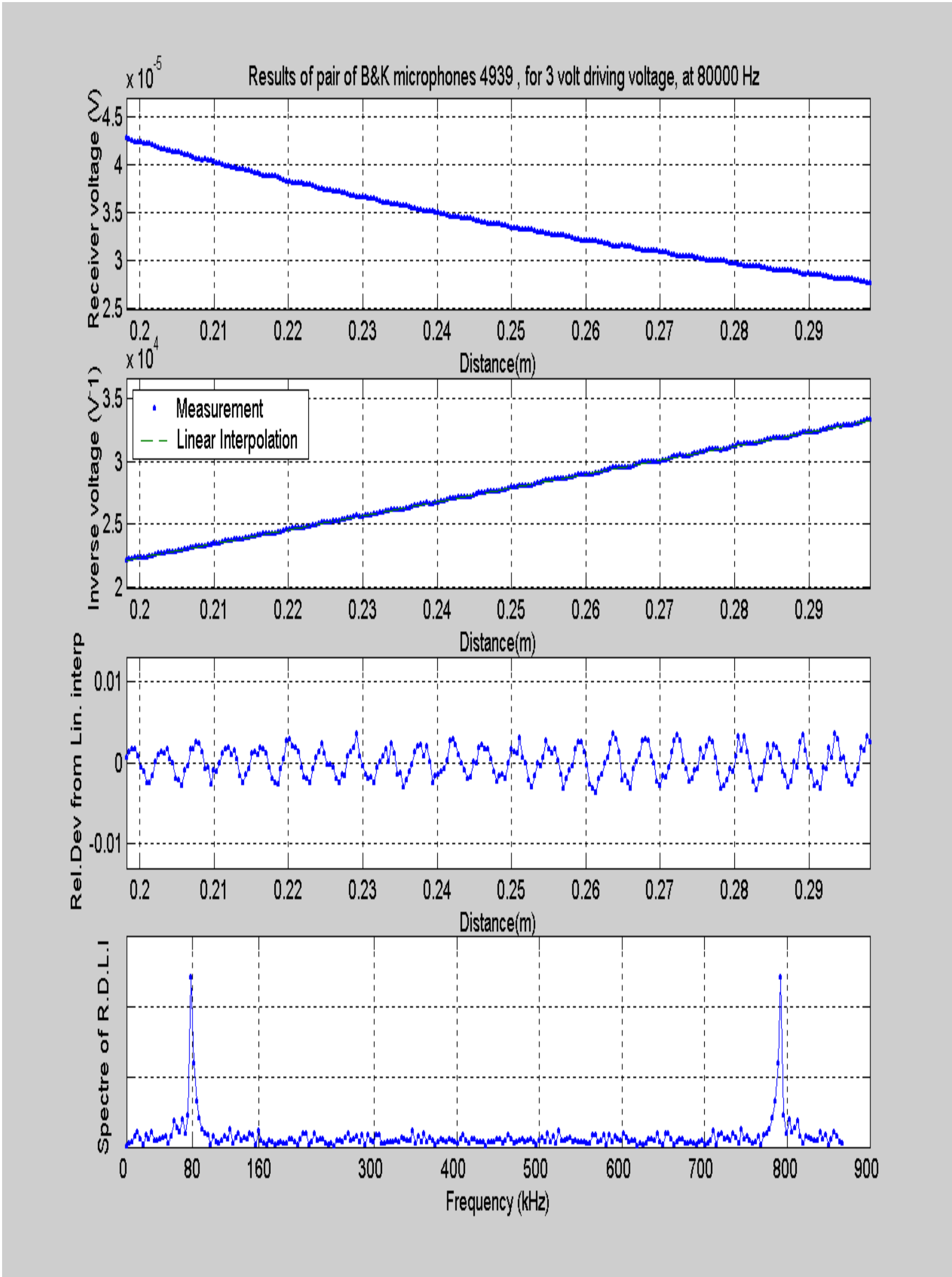


Figure III.9-g: Measurement results for microphones B&K 4939 at 80 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.40%. d) Spectrum of the deviations of the measured data from the inverse distance law.

a)
b)
c)
d)

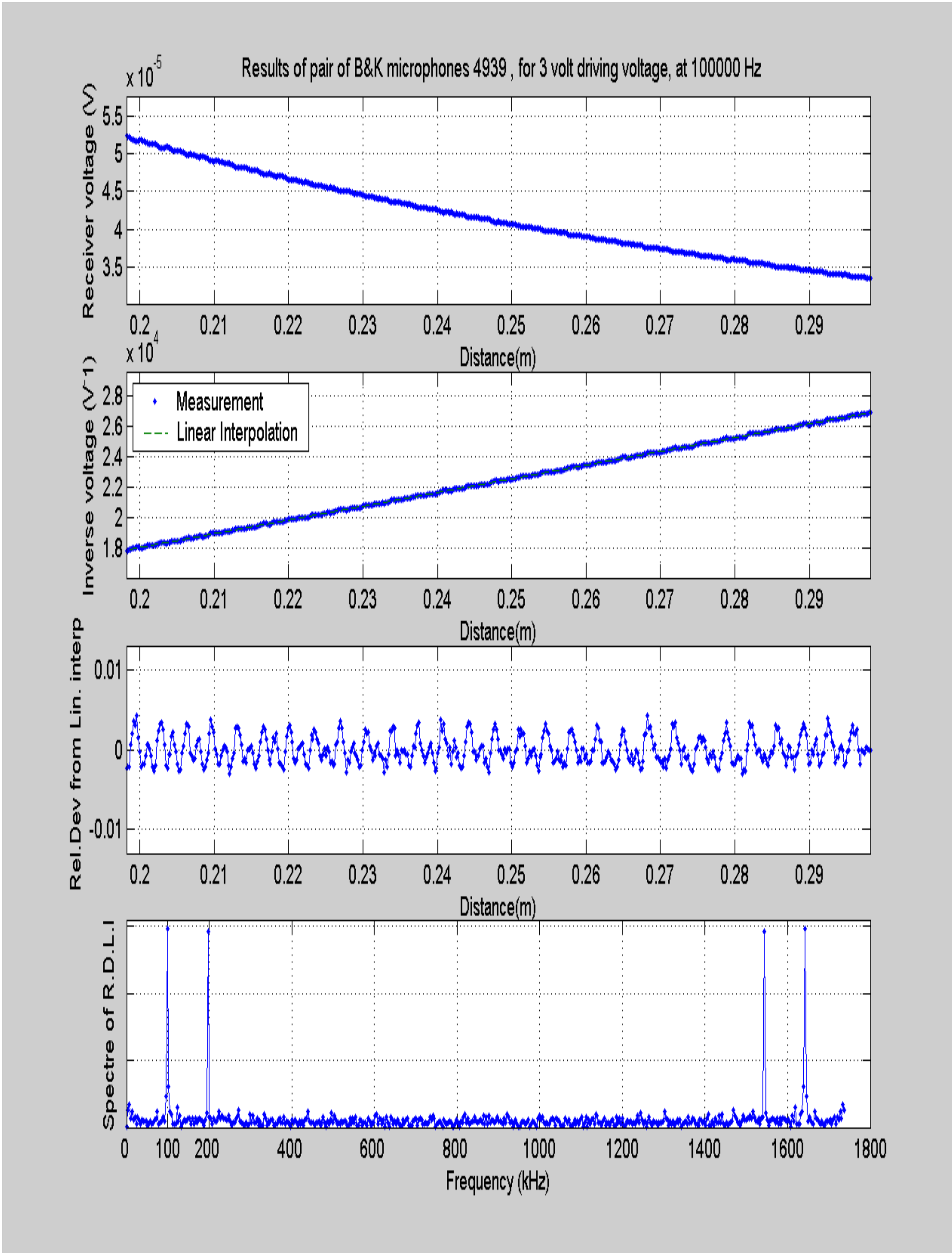


Figure III.9-h: Measurement results for microphones B&K 4939 at 100 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.43%. d) Spectrum of the deviations of the measured data from the inverse distance law.

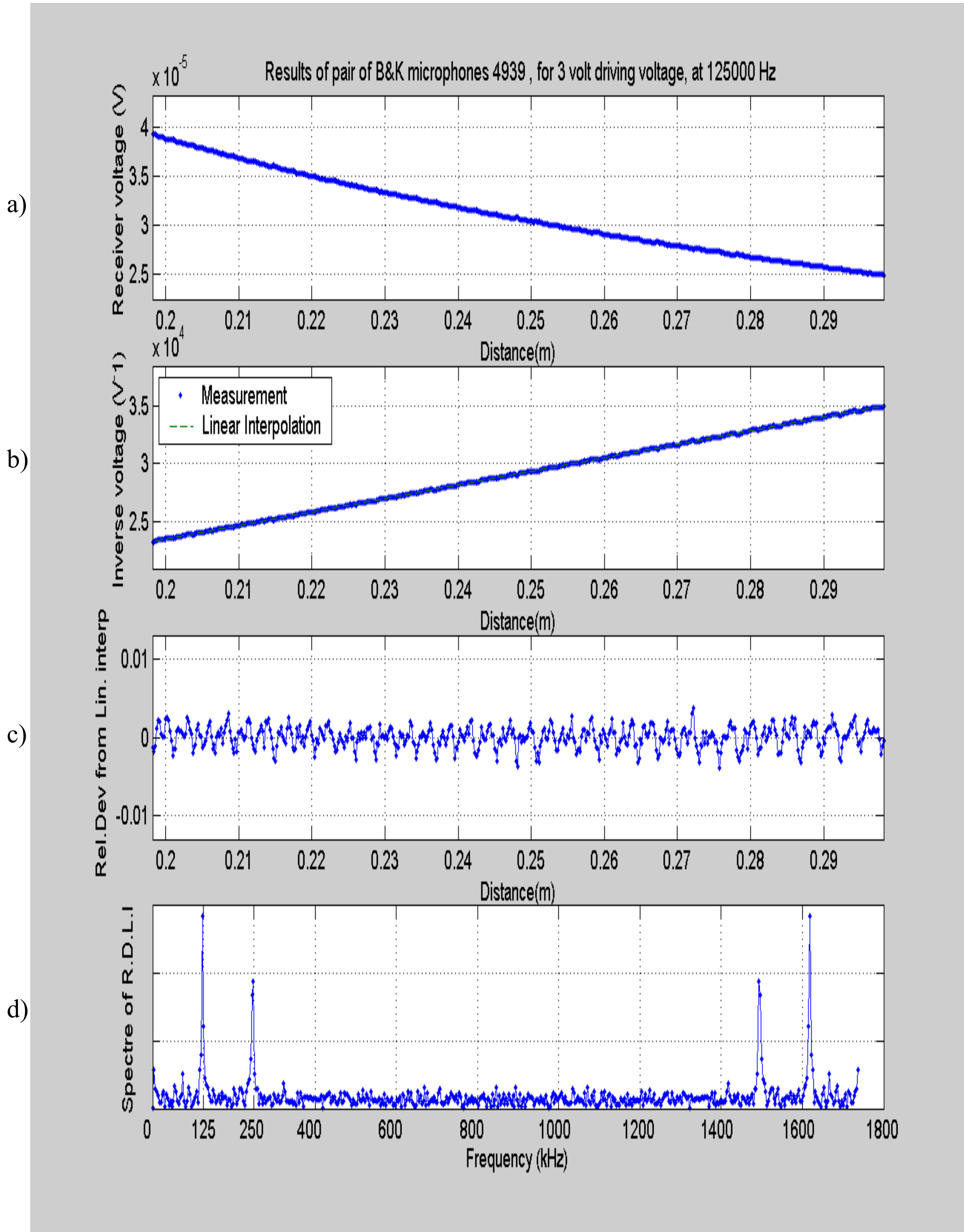


Figure III.9-i: Measurement results for microphones B&K 4939 at 125 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 0.38%. d) Spectrum of the deviations of the measured data from the inverse distance law.

a)
b)
c)
d)

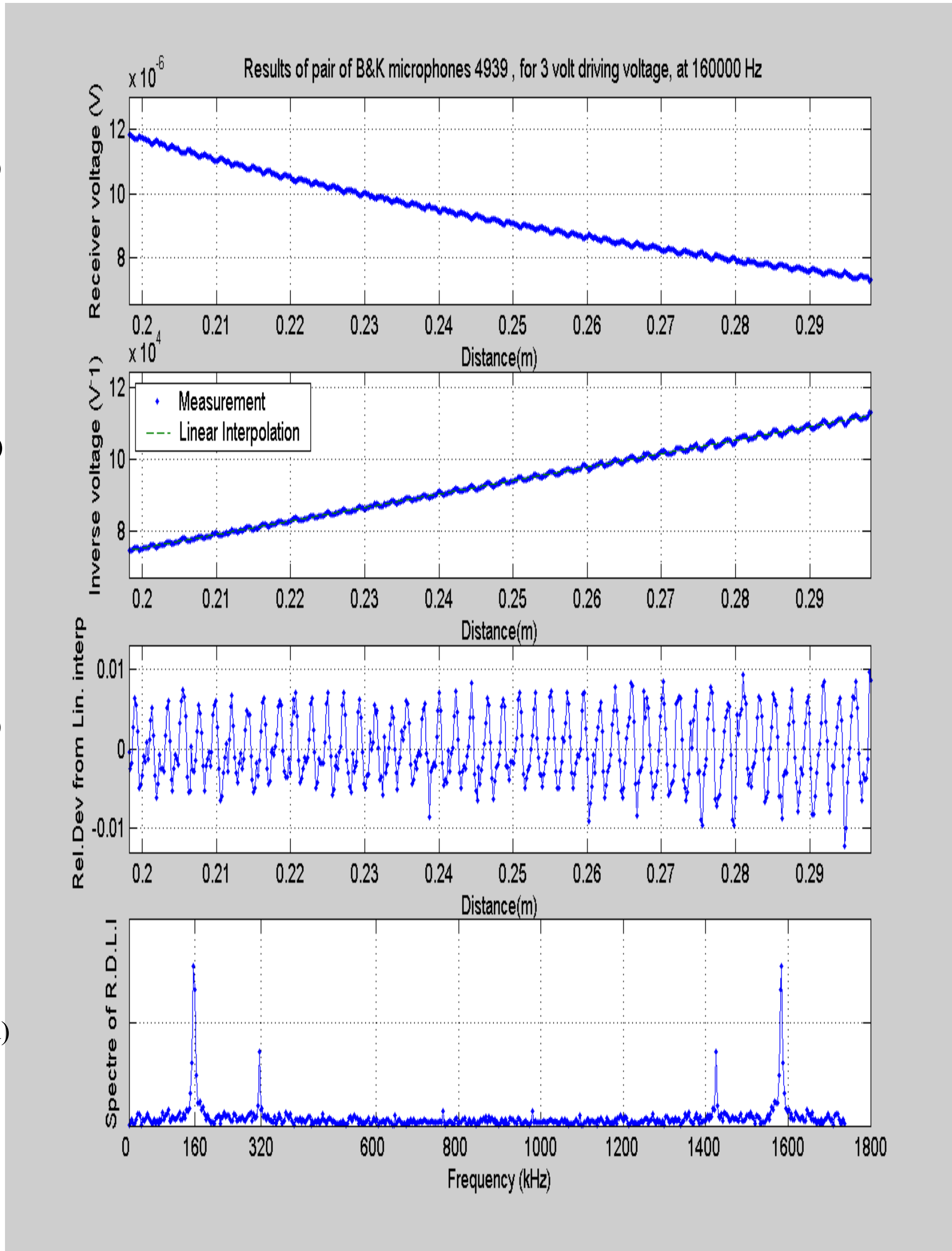


Figure III.9-j: Measurement results for microphones B&K 4939 at 160 kHz: a) open circuit voltage of the receiver microphone as a function of distance. b) Inverse of the open circuit voltage of the receiver microphone corrected for the air attenuation. c) The deviation of the measured data from the inverse distance law, which is less than 1.2%. d) Spectrum of the deviations of the measured data from the inverse distance law.

III.6 Distortion of the driving voltage

In this paragraph, the distortion of the ¼-inch condenser microphone is investigated; the measurement of the harmonics distortion is described and then compared to the theory.

When a microphone acts as a transmitter, the output signal will be distorted due to its principle of operation. Distortion produces undesirable output products and, as a result, the measured output at the fundamental frequency is too low, so, the calculated free-field sensitivity is too low, as well. The distortion is noticeable at sub-multiples of the driving frequency.

Figure III.10 shows the first-harmonic and second-harmonic distortion in percentage measured with a Distortion Analyzer Selective Level Meter SPM-11 (company Wandel & Goltermann) at a frequency of 25 kHz for a driving voltage range from 2 V to 20 V.

As can be seen, the distortion is first-harmonic and proportional to the driving voltage, for example, for 20 V driving voltage, the harmonic distortion is 9 percent.

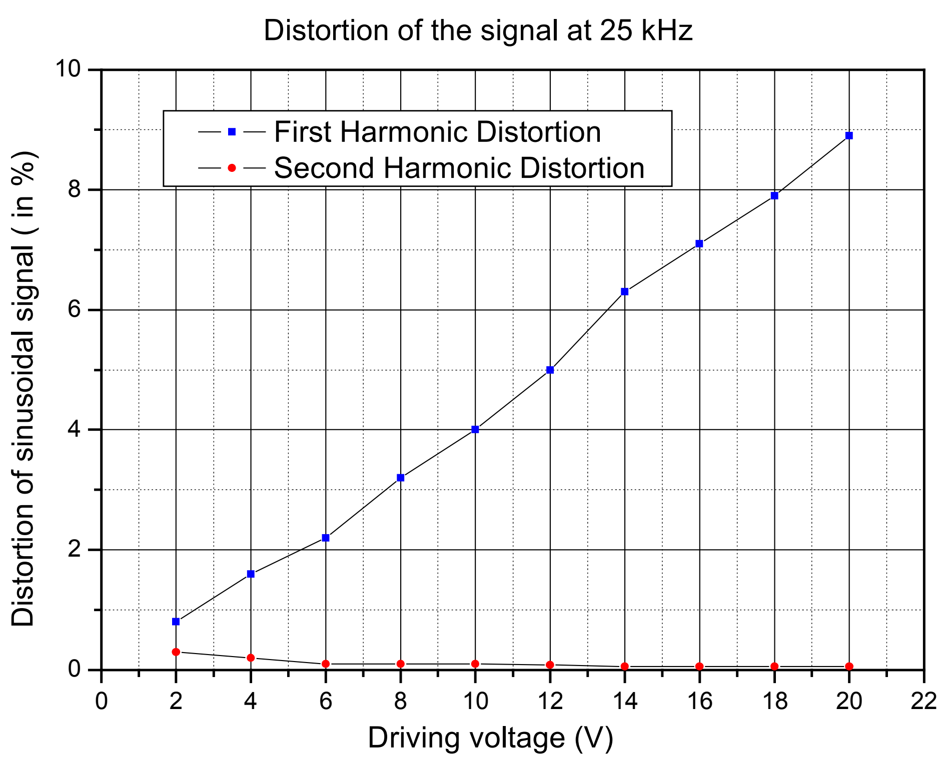


Figure III.10: Harmonic distortion of the driving signal at 25 kHz, function of the driving voltage.

A slight distortion increase was observed at 50 kHz. At higher frequencies, it was not possible to measure distortion because of the bandwidth limitation of the ¼-inch condenser microphones.

To minimize distortion, it is recommended to use a small driving voltage. In the present measurements, a driving voltage of less than 5 V is used, which corresponds to a distortion of less than 3 percent; this means that the sound pressure at the fundamental frequency is 0.01 dB lower than the total sound pressure.
According to [Frederiksen1977], when the electrical driving voltage is applied to the transmitter microphone, the force acting on the diaphragm can be given by:

$$F = \frac{{E_T}^2 C_T}{2d} = \frac{E^2{}_T \varepsilon A}{2d^2} \qquad \text{(III.4)}$$

$$F = \frac{(V_0 + e \sin \omega t)^2 \varepsilon A}{2d^2} \qquad \text{(III.5)}$$

where

V_0 is the polarizing voltage;
e the alternating driving voltage;

d the distance between diaphragm and back-plate;
ε the permittivity of air, and
A the surface of the diaphragm.

(III.2) can be written as:

$$F = \frac{\varepsilon A}{2d^2}\left({V_0}^2 + 2V_0 e \sin \omega t + e^2\left(\frac{1-\cos 2\omega t}{2}\right)\right) \qquad \text{(III.6)}$$

so the force has a static component as follows:

$$F_S = \frac{\varepsilon A}{2d^2}\left({V_0}^2 + e^2/2\right) \qquad \text{(III.7)}$$

and a dynamic component

$$F = \frac{\varepsilon A}{2d^2}\left(2V_0 e \sin \omega t - \frac{e^2 \cos 2\omega t}{2}\right) \qquad \text{(III.8)}$$

Thus, two components will be present in the output signal: the fundamental frequency and a second-harmonic distortion, which is the dominating distortion in such a system. The force distortion in percent can be calculated from

$$F = \frac{e}{4V_0} \times 100\ \% \qquad \text{(III.9)}$$

which can be written as

$$D_F = \frac{e_{rms}}{2\sqrt{2}V_0} \times 100\ \% \qquad \text{(III.10)}$$

where e_{rms} is the rms value of the alternating driving voltage

Due to the radiation properties, the distortion of the resulting sound pressure will be four times higher; (sound pressure is quadratic in frequency dependence) [Rasmussen2003], so the distortion in sound pressure can be given by

$$D_P = \sqrt{2}\,\frac{e_{rms}}{V_0} \times 100\ \% \qquad \text{(III.11)}$$

The comparison between measured and calculated distortion of a condenser microphone is represented in figure III.11.

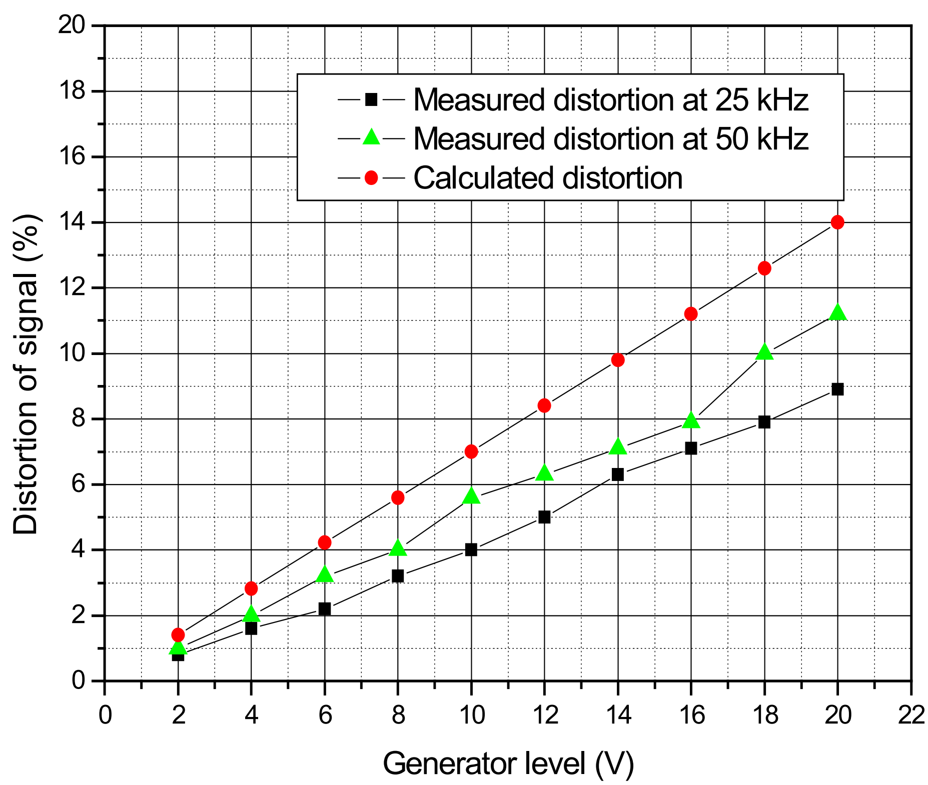


Figure III.11: Graph of the measured and calculated harmonic distortion function of the driving voltage.

III.7 Effects of static pressure

III.7.1 Electrostatic actuator calibration

The actuator method is well-suited for the measurement of relative frequency response, and has been used for a long time as a more simple, rapid and lower-cost method for determining the frequency response of microphones.

An electrostatic actuator is a metallic grid placed above the microphone diaphragm (figure III.12). A dc and ac voltages are supplied between the diaphragm and the actuator diaphragm, an electrostatic force is thus produced and acts on the microphone diaphragm as a sound pressure. In this section, the electrostatic actuator calibration of ¼-inch condenser microphones B&K 4939 is discussed for the audible and ultrasonic frequency range.

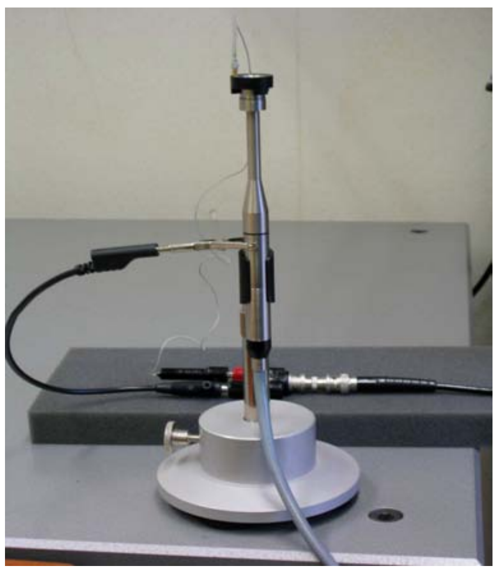


Figure III.12: Electrostatic actuator.

An electrostatic actuator B&K UA0033 is used for the calibration of a ¼-inch microphone B&K 4939 in the audio and ultrasonic frequency range. The experimental arrangement of the actuator measurement is shown in figure III.13. An actuator voltage supply B&K WB 0736 WH 2942 generates 800 V dc and 30 V ac supplied to an actuator used with an adaptor for ¼-inch condenser microphones. The free-field microphone B&K 4939 is used in this measurement with an adaptor ½-inch to ¼-inch B&K UA0035.

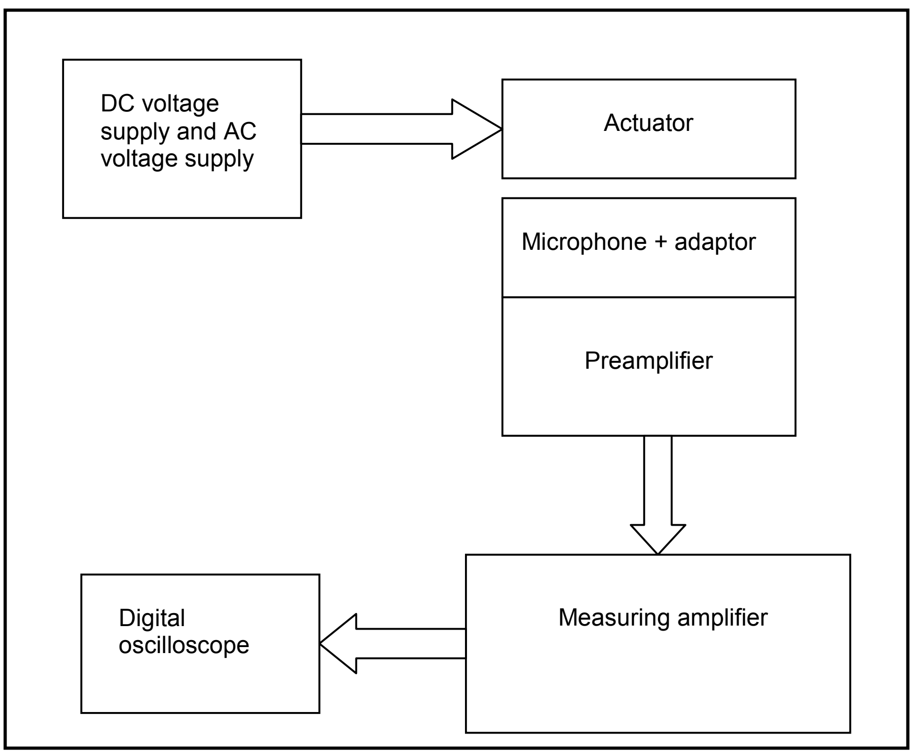


Figure III.13: Photo and schematic diagram of the measurement set-up for electrostatic actuator calibration.

Figure III.14 shows the actuator response for a ¼-inch microphone B&K 4939 in the frequency range from 100 Hz to 200 kHz relative to the actuator response at 250 Hz.

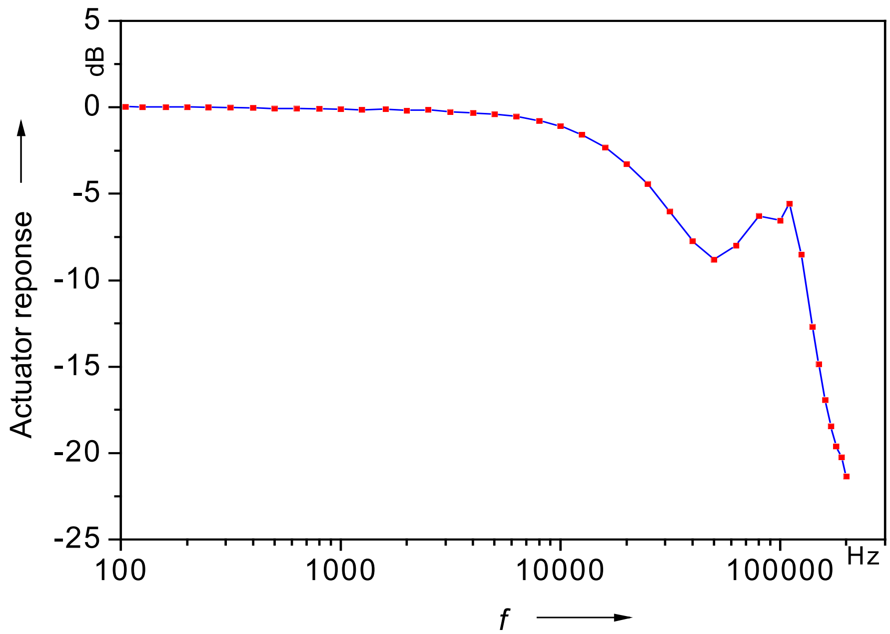


Figure III.14: Electrostatic actuator response of microphones B&K 4939.

III.7.2 Static pressure coefficients

The sensitivity of condenser microphones depends on the environmental conditions (static pressure, temperature). Variations in the environmental conditions will change the acoustic properties of the air between the diaphragm and the back-plate of the condenser microphone. To achieve a precise and repeatable free-field reciprocity calibration of ¼-inch condenser microphones, the measurements should be carried out in a controlled environment (23 °C and 101.325 kPa). Because of the variation of the static pressure inside the anechoic room, a microphone sensitivity correction for the changes in static pressure is required.

The correction for the influence of the static pressure on the sensitivity levels of 1-inch and ½-inch condenser microphones have been studied by K. Rassmusen [Rassmusen1993] [Rassmusen1999] [Rassmusen2001] and G. Wong [Wu1999] [Wong2005]. G. Wong [Wong2005], reported that, over the static pressure range from 94 kPa to 106 kPa, the sensitivity levels of the ½-inch microphone of type B&K 4180 and GRAS 40AG changed by 0.05 dB at 1 kHz and 0.12 dB at 20 kHz.
This paragraph deals with the determination of the free-field sensitivity correction of ¼-inch microphone, resulting from changes in static pressure.

The change in the output voltage of three ¼-inch microphones of type B&K 4939 (SN 2389646, 2389698 and 2389701) was measured by means of the electrostatic actuator method (described in the previous paragraph) at five static pressures in the range from 90 kPa to 106 kPa, in a closed pressure vessel (figure III.15).

Figure III.15: Photo of the static pressure vessel.

The microphone sensitivity corrections for each frequency were calculated for these pressures in the frequency range from 0.25 kHz to 150 kHz, by subtraction of the sensitivity at the reference static pressure of 101.325 kPa from the sensitivities at these pressures (figure III.16). From 90 kPa to 105 kPa, at 5 kHz, the variation of the sensitivity is about 0.1 dB and at 150 kHz approximately 0.45 dB. The maximum variation was observed at 95 kHz, by approx. 2.95 dB.

The pressure coefficients shown in figure III.17 are determined at each frequency by a straight-line interpolation of the calculated sensitivities, defined as gradients of these lines and expressed in dB/kPa. The straight line was fitted by the method of ordinary least squares programmed with Matlab. The maximum pressure coefficient for the three microphones is located at 95 kHz; the corresponding maximum is about 0.2 dB/kPa.

The maximum standard deviation of the mean value of the pressure coefficients of the three microphones is 0.013 dB/kPa, observed at frequencies of 95 kHz and 100 kHz (table III.1).

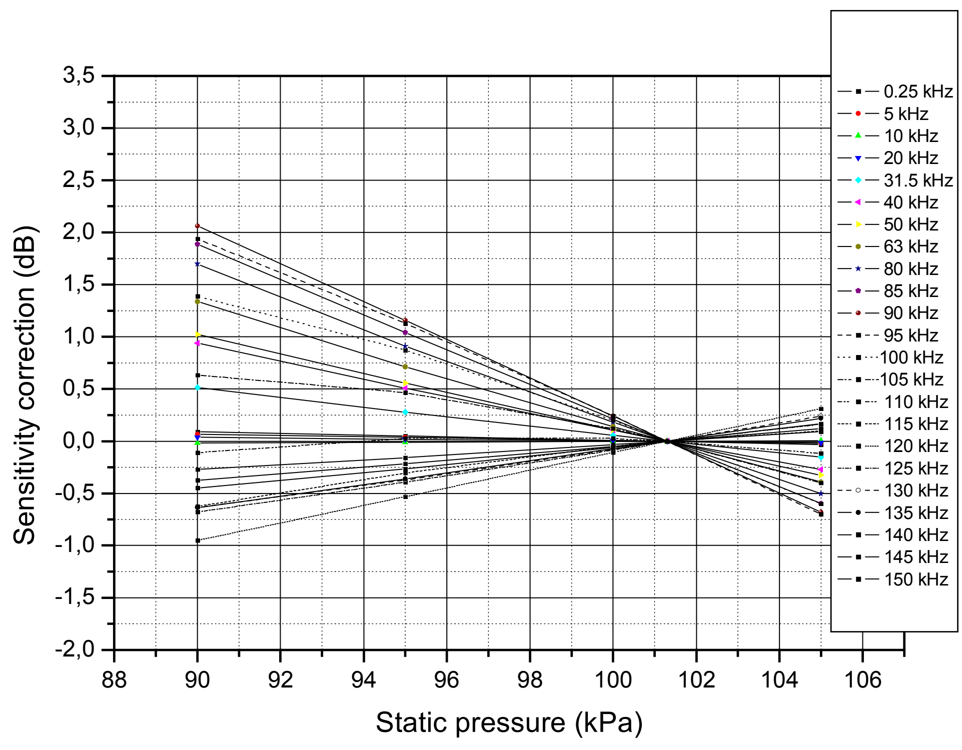


Figure III.16: Sensitivity correction due to static pressure variation at various frequencies.

In order to know the static pressure coefficients at other frequencies, and to derive an expression valid for this type of microphones, the results of the pressure coefficients variation over frequency were approximated by a polynomial interpolation of fifteenth order for each microphone. The static pressure coefficients can be calculated from the empirical equation

$$\delta_{Static\,Pressure} = a_0 + a_1 \cdot f + a_2 \cdot f^2 + ... + a_{15} \cdot f^{15} \qquad \text{(III.10)}$$

Table III.2 gives the average value for the resulting polynomial coefficients a_0-a_{15}. The graph of this equation of the static pressure coefficients is shown in figure III.17

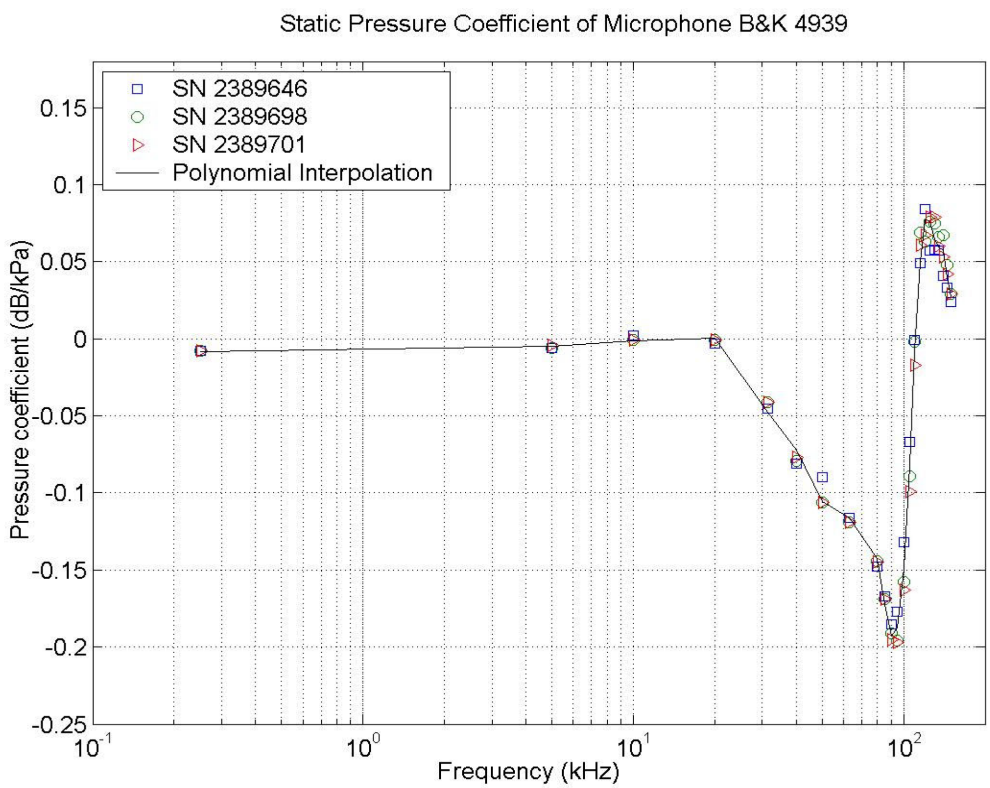


Figure III.17: Variation of the static pressure coefficients with frequency.

Frequency (kHz)	Static pressure coefficient for microphones B&K 4939 (dB) SN 2389698	SN 2389646	SN 2389701	Mean	Stdv.
0.25	-0.008	-0.008	-0.008	-0.008	0
5	-0.006	-0.006	-0.004	-0.005	0.0009
10	-0.001	0.002	-0.001	0	0.0014
20	-0.001	-0.003	-0.001	-0.0016	0.0009
31.5	-0.041	-0.045	-0.041	-0.0423	0.0018
40	-0.079	-0.081	-0.077	-0.079	0.0016
50	-0.106	-0.09	-0.106	-0.1006	0.0075
63	-0.119	-0.116	-0.119	-0.118	0.0014
80	-0.144	-0.148	-0.145	-0.1456	0.0016
85	-0.169	-0.167	-0.169	-0.1683	0.0009
90	-0.191	-0.185	-0.195	-0.1903	0.0041
95	-0.196	-0.177	-0.197	-0.19	0.0092
100	-0.158	-0.132	-0.163	-0.151	0.0135
105	-0.089	-0.067	-0.099	-0.085	0.0133
110	-0.002	-0.001	-0.017	-0.0066	0.0073
115	0.069	0.049	0.061	0.0596	0.0082
120	0.063	0.084	0.067	0.0713	0.0091
125	0.076	0.057	0.079	0.0706	0.0097
130	0.075	0.058	0.079	0.0706	0.0091
135	0.066	0.057	0.06	0.061	0.0037
140	0.067	0.041	0.053	0.0536	0.0106
145	0.048	0.033	0.042	0.041	0.0061
150	0.029	0.024	0.029	0.0273	0.0023

Table III.1: Static pressure coefficients for microphones B&K 4939.

Coefficient a_i	
a_1	-2.40 10^{-25}
a_2	2.64 10^{-22}
a_3	-1,29 10^{-19}
a_4	3,71 10^{-17}
a_5	-6,94 10^{-15}
a_6	8,87 10^{-13}
a_7	-7,92 10^{-11}
a_8	4,96 10^{-9}
a_9	-2.16 10^{-7}
a_{10}	6.36 10^{-6}
a_{11}	-1.20 10^{-4}
a_{12}	1.36 10^{-3}
a_{13}	-8.00 10^{-3}
a_{14}	1.91 10^{-2}
a_{15}	-1.24 10^{-2}

Table III.2: Polynomial coefficients for calculating the static pressure coefficient.

III.8 Acoustic center of ¼ inch condenser microphones

This paragraph describes a method permitting the determination of the acoustic center of condenser microphones, and presents the results for ¼-inch condenser microphones.

A precise measurement of the free-field sensitivity of condenser microphones requires the knowledge of the acoustic center of the microphone. Few works have been published on the acoustic center of condenser microphones of 1-inch and ½-inch condenser microphones [Rassmussen1973] [Rassmussen1993] [Juhl1994] [Barham1995] [Wagner1998] [Jacobsen2004]. However, no works providing values of the acoustic center of ¼-inch condenser microphones have been published.

The determination of the acoustic center can be carried out by means of a linear regression for the voltage of the receiver microphone as function of distance.
From equation II.46 it can be seen that the sound pressure generated by the transmitter microphone is inversely proportional to the distance. If the receiver microphone is a point source, which does not disturb the sound field, and is positioned at a distance *d*, the output voltage corrected for absorption will be inversely proportional to the distance:

$$E_r e^{\alpha d_{12}} = \frac{A}{d_{12}} = \frac{A}{d-(d_{ac1}+d_{ac2})} \qquad \text{(III.13)}$$

where
A is a linear proportionality constant;
d_{12} the distance between the acoustic centers of transmitter microphone and receiver microphone;
α the air attenuation;
d the distance between the diaphragms of the transmitter and receiver microphones;
d_{ac1} the distance between the diaphragm of the transmitter microphone and its acoustic center, and
d_{ac2} the distance between the diaphragm of the receiver microphone and its acoustic center.

It can be assumed that the distance between the microphones is large compared with the sum of the acoustic center distance ($d_{ac1}+d_{ac2}$) so that the factor $e^{\alpha d_{12}}$ can be approximated to $e^{\alpha d}$, this yields to:

$$E_r e^{\alpha d} = \frac{A}{d-(d_{ac1}+d_{ac2})} \qquad \text{(III.14)}$$

Inverting Equation (III.14) shows its linear dependence on the distance *d* between the diaphragms, which can be written as:

$$\frac{1}{E_r e^{\alpha d}} = \frac{d}{A} - \frac{(d_{ac1} + d_{ac2})}{A} \tag{III.15}$$

Let the sum of both acoustic center distances of the transmitter and receiver microphones be $d_{ac12} = (d_{ac1} + d_{ac2})$, so that equation (III.13) becomes

$$\frac{1}{E_r e^{\alpha d}} = \frac{d}{A} - \frac{d_{ac12}}{A} \tag{III.16}$$

this can be written as a straight-line equation

$$\frac{1}{E_r e^{\alpha d}} = a\,d + b \tag{III.17}$$

where the slope *a* and y-axis intercept *b* are given by

$$a = \frac{1}{A} \tag{III.18}$$

$$b = -\frac{d_{ac12}}{A} \tag{III.19}$$

Therefore, the sum of the acoustic center d_{ac12} can be derived from the slope *a* and the y-axis intercept *b*, as

$$d_{ac12} = -\frac{b}{2\,a} \tag{III.20}$$

By using three pairs of microphones, the acoustic center of microphone 1 can be given from

$$d_{ac1} = \frac{d_{ac12} + d_{ac31} - d_{ac23}}{2} \tag{III.21}$$

For the three microphone pairs, for each frequency, the measured values of the open-circuit voltage were corrected for the attenuation of sound pressure, over the distance range of the measurement.
A straight-line was fitted by the method of ordinary least squares programmed using Matlab. A Small deviation from the linear model was caused by effects of standing waves and crosstalk, so the measurement distance is therefore chosen where theses effects were minimal, as described in part III.5.

The results for the acoustic centers of three condenser microphones B&K 4939 are presented in figure III.18 and table III.3.

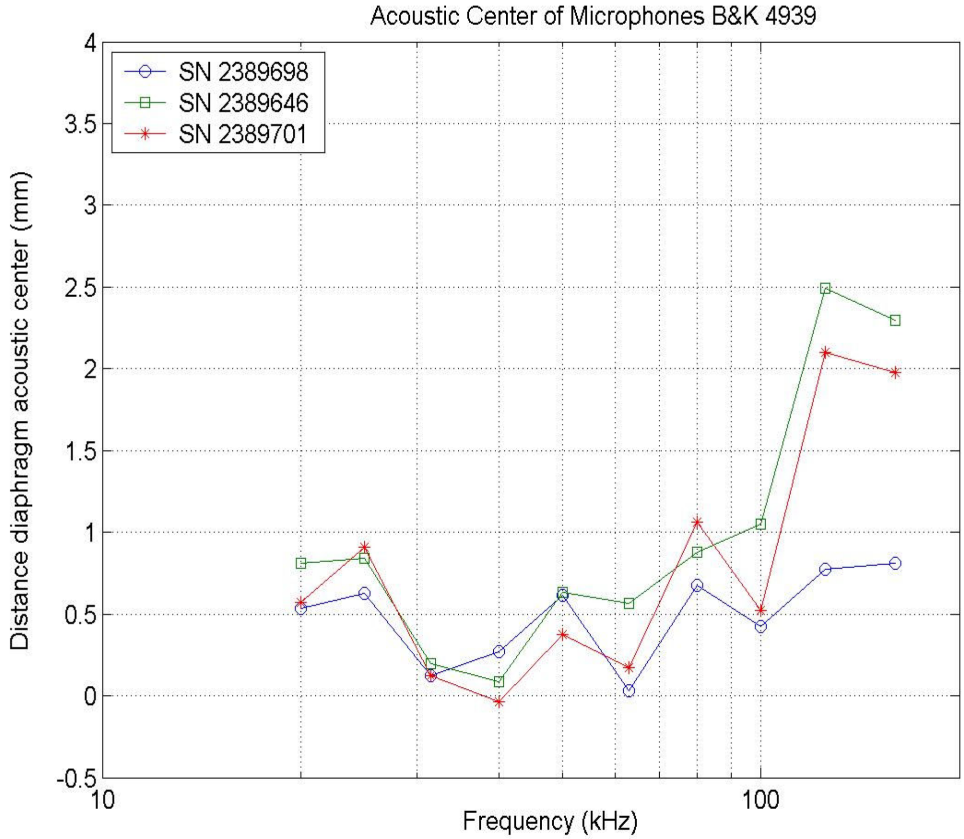


Figure III.18: Variation of the acoustic center of condenser microphone B&K 4939 with frequency.

Frequency (kHz)	Acoustic center for microphones B&K 4939 (mm) SN 2389698	SN 2389646	SN 2389701	Mean	Stdv
20	0.53	0.81	0.57	0.63	0.12
25	0.62	0.84	0.90	0.79	0.12
31.5	0.12	0.19	0.12	0.14	0.03
40	0.27	0.08	-0.03	0.10	0.12
50	0.61	0.63	0.37	0.53	0.11
63	0.03	0.56	0.16	0.25	0.22
80	0.67	0.88	1.06	0.87	0.15
100	0.42	1.05	0.52	0.66	0.27
125	0.77	2.49	2.09	1.78	0.73
160	0.80	2.29	1.97	1.69	0.63

Table III.3: Acoustic center for microphones B&K 4939.

III.9 Computer control of the measurement set-up

Due to the time-consuming character of the measurement performed at several frequencies, over a number of distances, which is high at higher frequencies, 512 distances for frequencies above 80 kHz, and also in order to improve the repeatability of measurements, it was necessary to realize an automated set-up controlled by a computer. A computer in conjunction with an IEEE488 Standard Instrument Control Bus (GPIB) controls the reciprocity calibration system. The programs permitting the automation of all aspects of the measurement set-up from the instrumentation control to the collection of the measurement calibration data were coded and compiled with LABWINDOWS under Microsoft Windows XP. The data of the measurement results were then imported to MATLAB, in which analysis, calculations and presentation of the measurement results were performed.

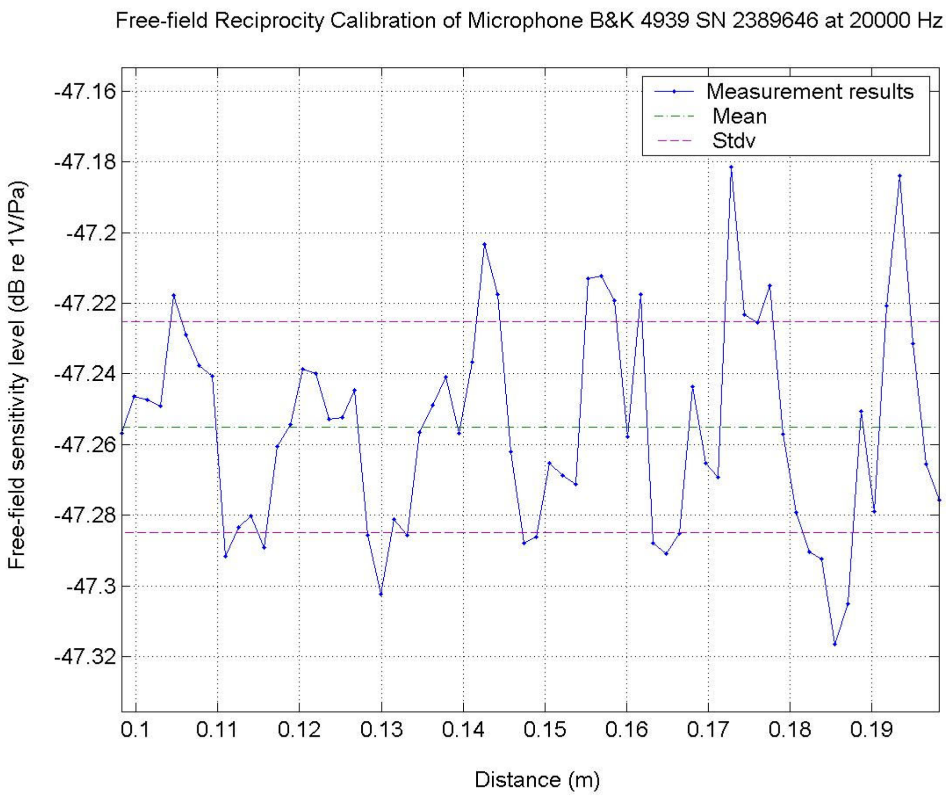
III.10 Results of the measurement of the free-field sensitivity

A free-field reciprocity calibration has been performed with three ¼-inch condenser microphones B&K 4939 (SN: 2389646, 2389698, and 2389701). For each frequency, from 20 kHz to 160 kHz (1/3-octave frequencies), first the amplification of the receiver part of the circuit was determined by the insert-voltage technique. The driving voltage of the transmitter microphone was 3 V to avoid the problem of distortion (see paragraph III.6).

For each frequency, the driving voltage and the open-circuit voltage of the receiver microphone were measured for a pair of microphones. The measurements of the open-circuit voltage of the receiver microphone were performed over the distance ranges given in paragraph III.5. The measurements were carried out at least at 64 distances.

For each frequency, the product of the sensitivities of each of the three pairs of microphones (Eq. III.1) is determined for the range of distances discussed in paragraph III.5, from the measured capacitance of the transmitter microphone, the calculated density and the attenuation of sound pressure for the environmental conditions of measurements, the distance between the acoustic centers of the transmitter and receiver microphones determined as described in part III.8. The air temperature inside the anechoic room is monitored by a resistance thermometer and the temperature of the whole laboratory is kept constant at 23±0.5 °C. Therefore, no temperature correction was applied to the sensitivity product. Using the static pressure coefficient studied and tabulated in paragraph III.7.2, a correction of the product of the sensitivities was applied referred to the static pressure of 101.325 kPa.

The results of the measured free-field sensitivity of microphones are shown in table III.4, figure III.19 and figure III.20. The values were obtained by averaging the individual measurements at the number of distances.



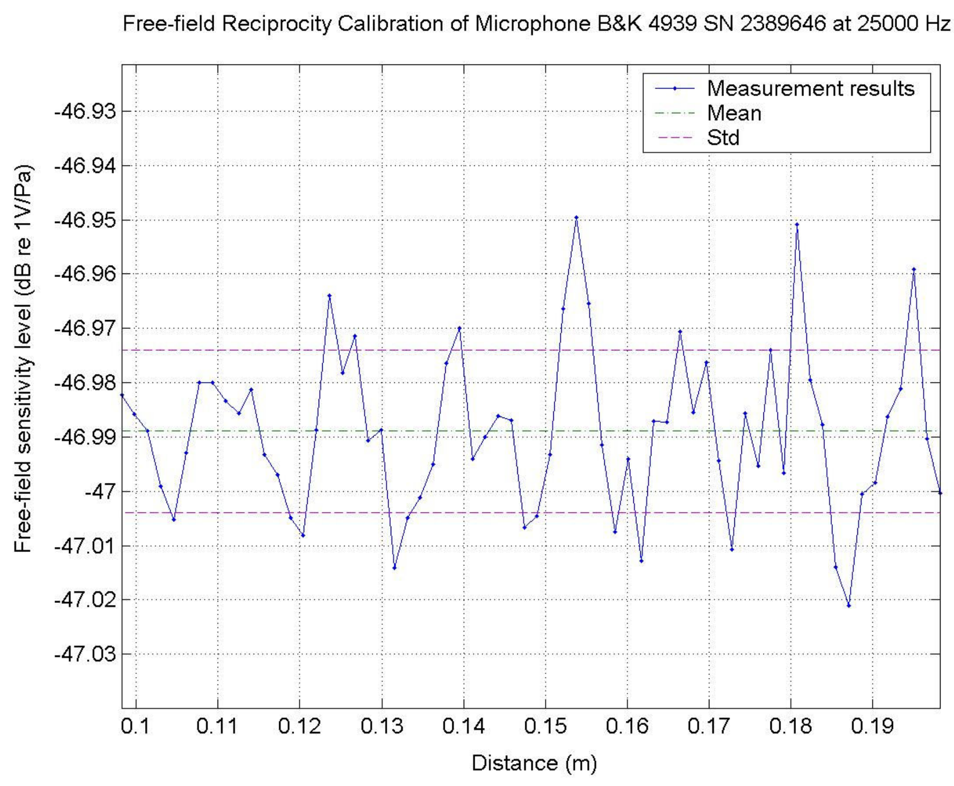
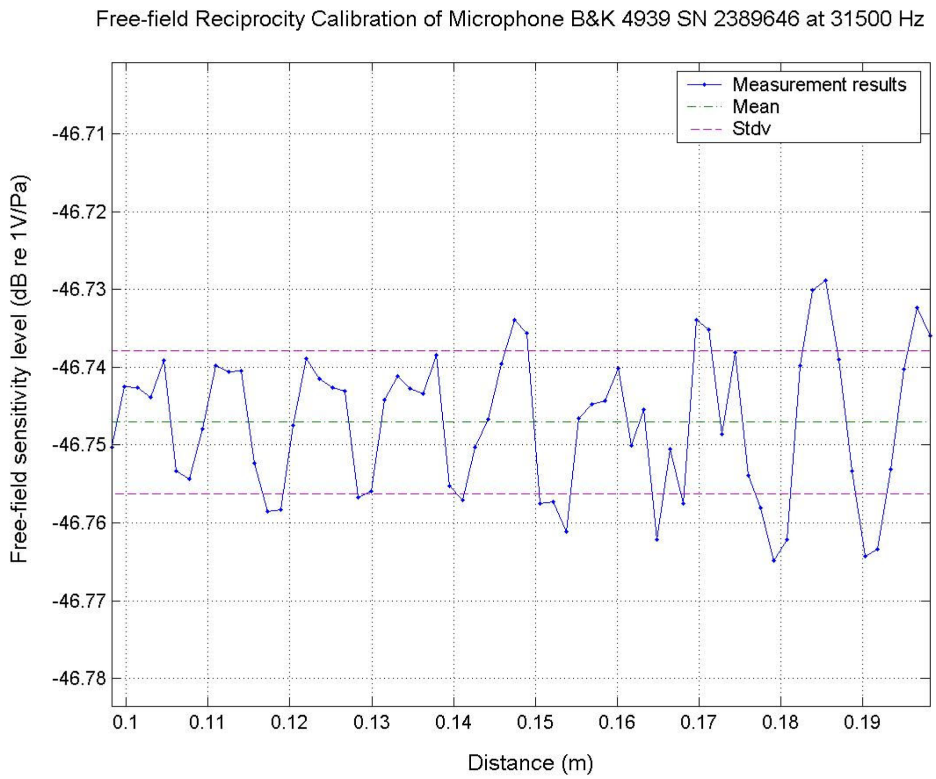


Figure III-19-a: Measurement results of free-field sensitivity as function of distance at 20 kHz and 25 kHz.



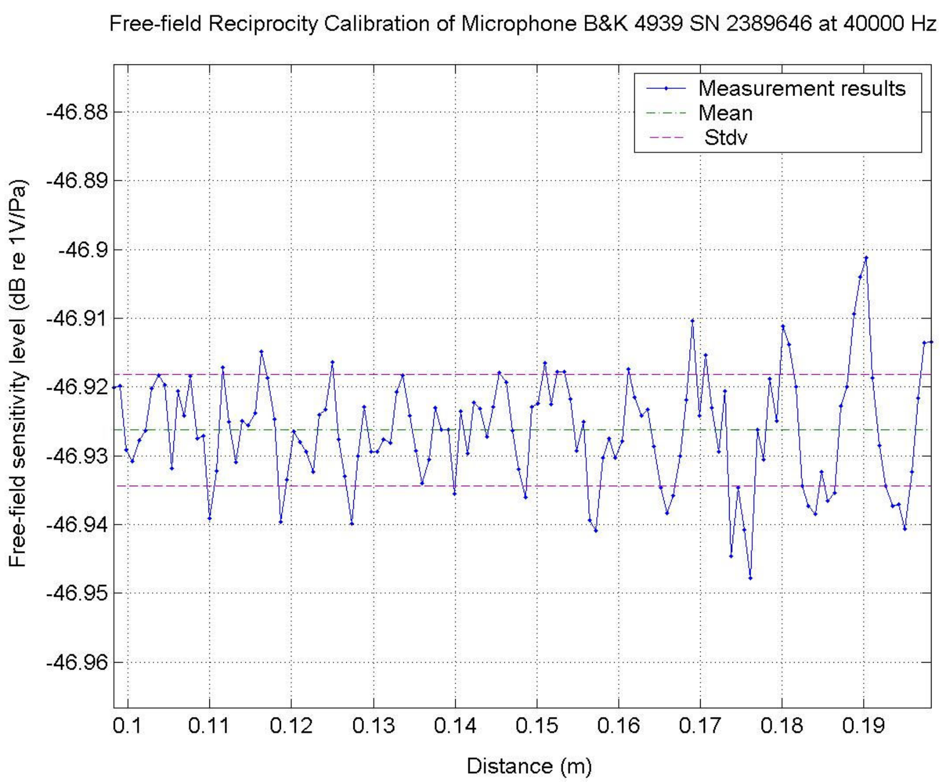
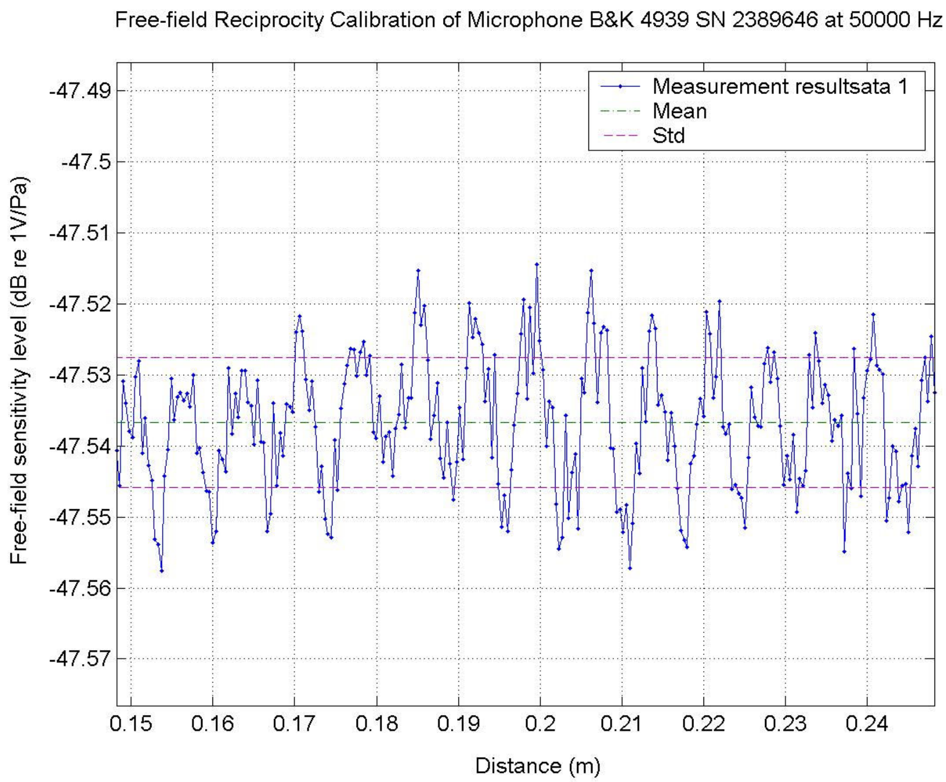


Figure III-19b: Measurement results of free-field sensitivity as function of distance at 31.5 kHz and 40 kHz.



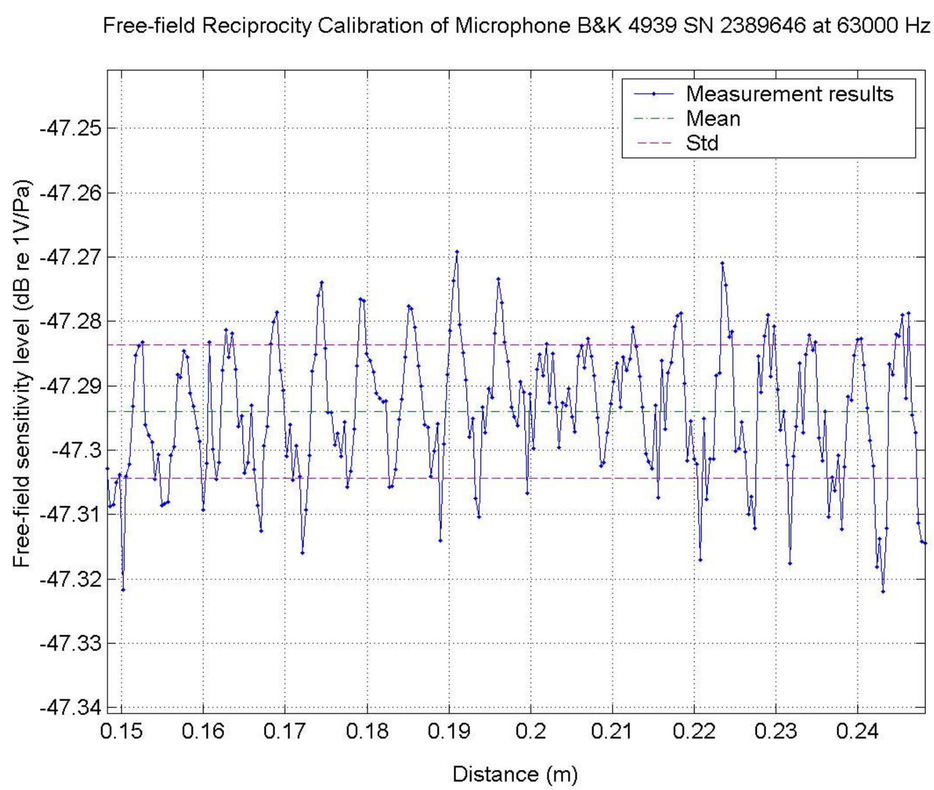
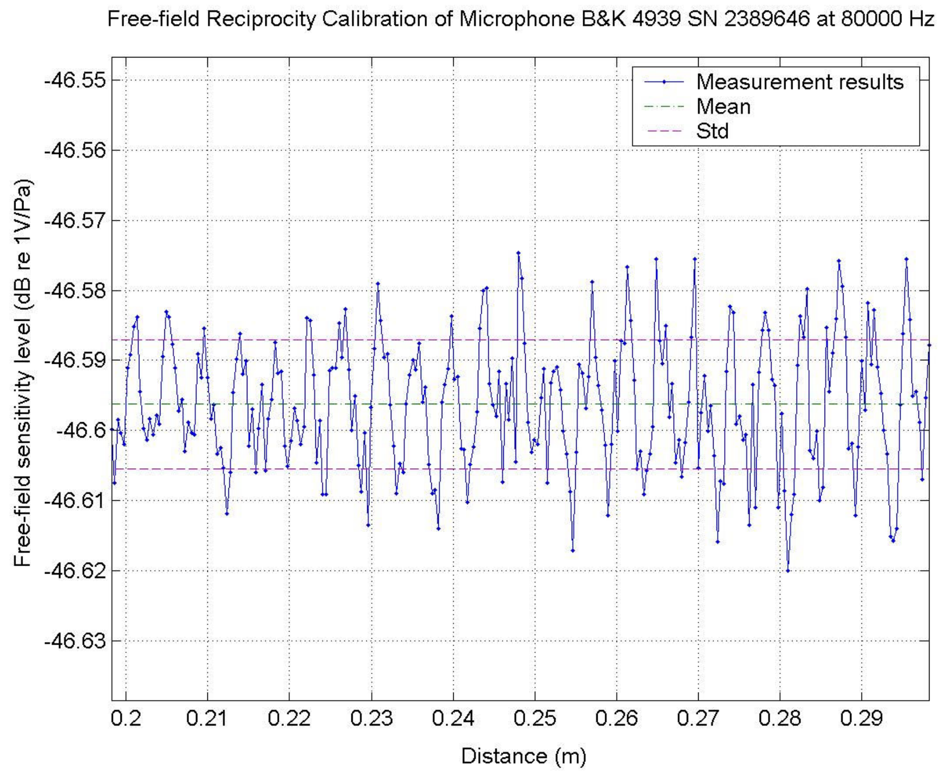


Figure III-19c: Measurement results of free-field sensitivity as function of distance at 50 kHz and 63 kHz.



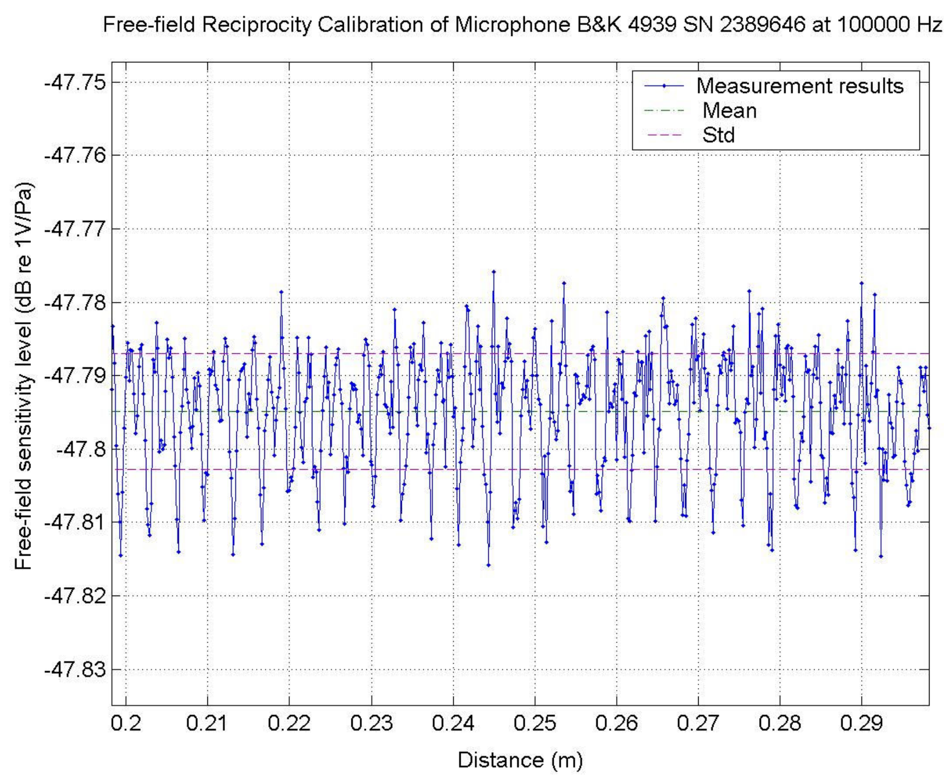
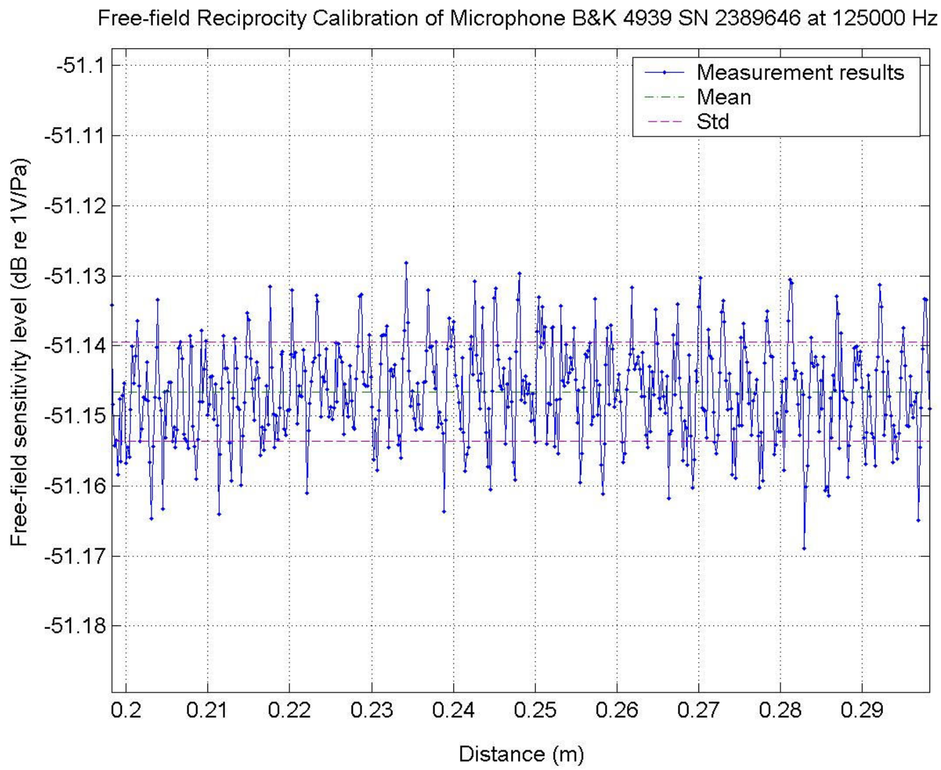


Figure III-19d: Measurement results of free-field sensitivity as function of distance at 80 kHz and 100 kHz.



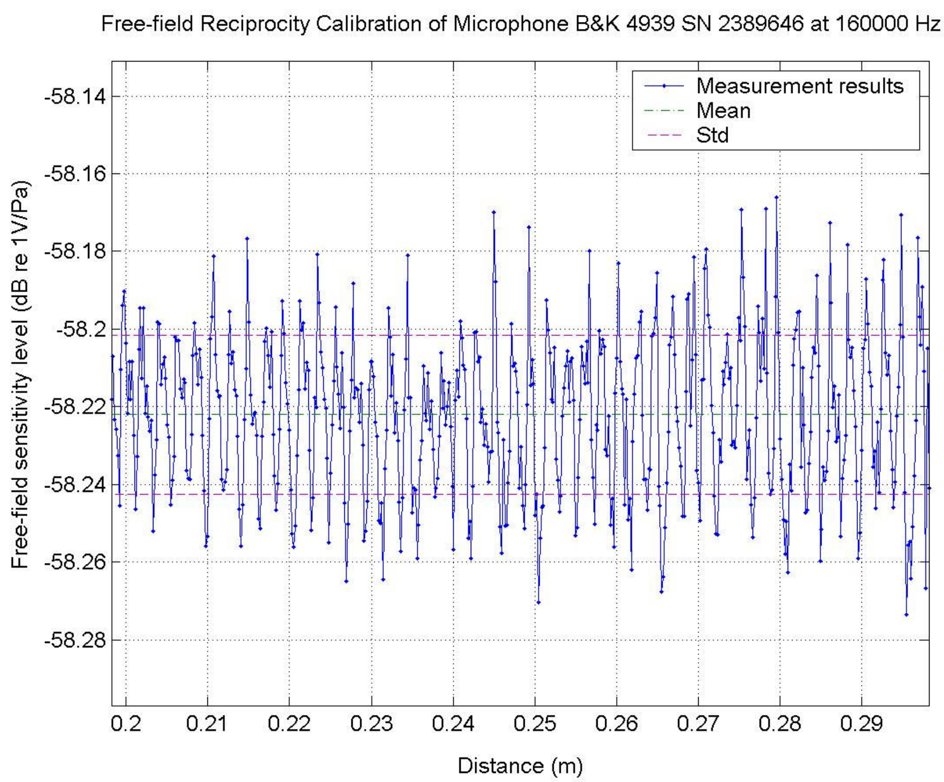


Figure III-19e: Measurement results of free-field sensitivity as function of distance at 125 kHz and 160 kHz.

Frequency (kHz)	N° Distances	Measured free-field sensitivity level of microphones B&K 4939 (dB re 1V/Pa)					
		SN 2389698		SN 2389646		SN 2389701	
		Mean	Stdv.	Mean	Stdv.	Mean	Stdv.
20	64	47.162	0.023	47.255	0.029	47.206	0.025
25	64	47.034	0.011	46.989	0.014	47.08	0.012
31.5	64	46.992	0.007	46.747	0.009	46.973	0.006
40	128	47.446	0.007	46.926	0.008	47.431	0.009
50	256	48.043	0.008	47.537	0.009	47.814	0.010
63	256	48.098	0.013	47.294	0.010	47.946	0.013
80	256	47.327	0.009	46.596	0.009	47.281	0.009
100	512	48.215	0.008	47.795	0.007	48.193	0.007
125	512	51.082	0.007	51.147	0.007	50.564	0.007
160	512	58.454	0.024	58.222	0.020	58.102	0.023

Table III.4: Measured values for the free-field sensitivity of microphones B&K 4939.

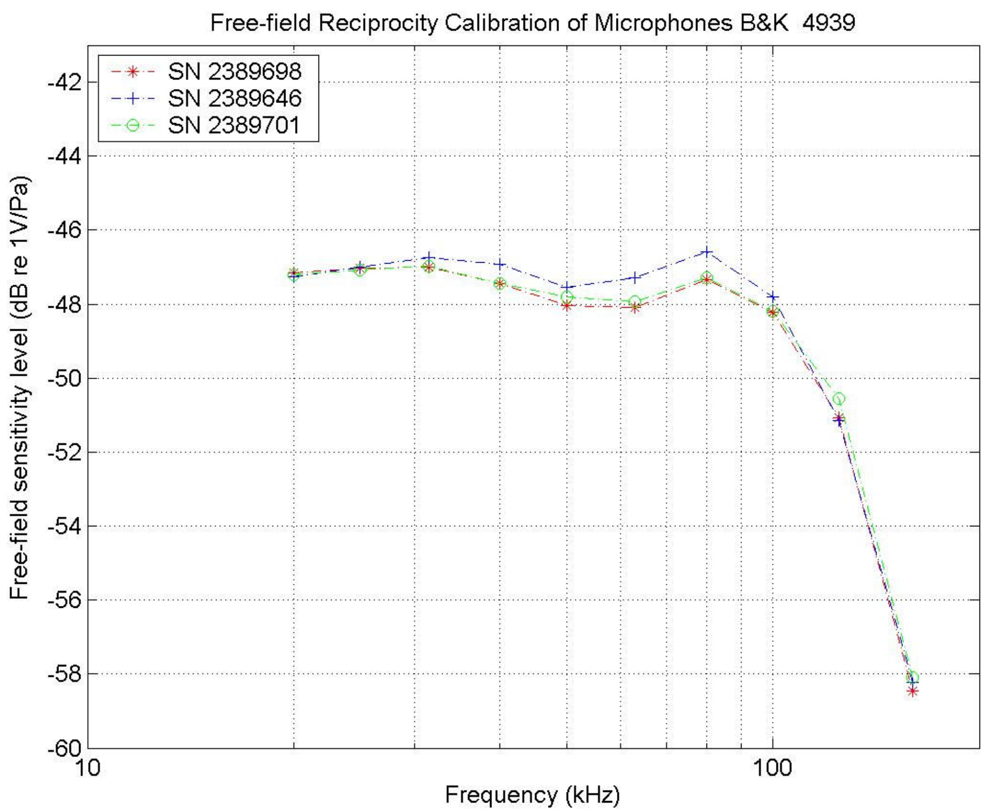


Figure III.20: Measured values for the free-field sensitivity of condenser microphones B&K 4939 as function of frequency.

III.11 Reproducibility of measurement results

The reproducibility study shows that the standard deviation of the measured sensitivity for three measurements is less than 0.04 dB for the whole frequency range (table III.5 and figure III.21).

Frequency (kHz)	Reproducibility of three measured free-field sensitivity of microphones B&K 4939 SN 2389646 (dB) Measurement 1	Measurement 2	Measurement 3	Mean	Stdv.
20	47.25	47.25	47.21	47.24	0.019
25	46.98	47.02	47.02	47.01	0.017
31.5	46.74	46.76	46.77	46.76	0.013
40	46.92	46.92	46.97	46.94	0.022
50	47.53	47.50	47.49	47.51	0.017
63	47.29	47.24	47.25	47.26	0.021
80	46.59	46.59	46.59	46.59	0.001
100	47.79	47.72	47.71	47.74	0.036
125	51.14	51.13	51.08	51.12	0.025
160	58.22	58.21	58.13	58.19	0.037

Table III.5: Reproducibility of the measured free-field sensitivity of microphones B&K 4939.

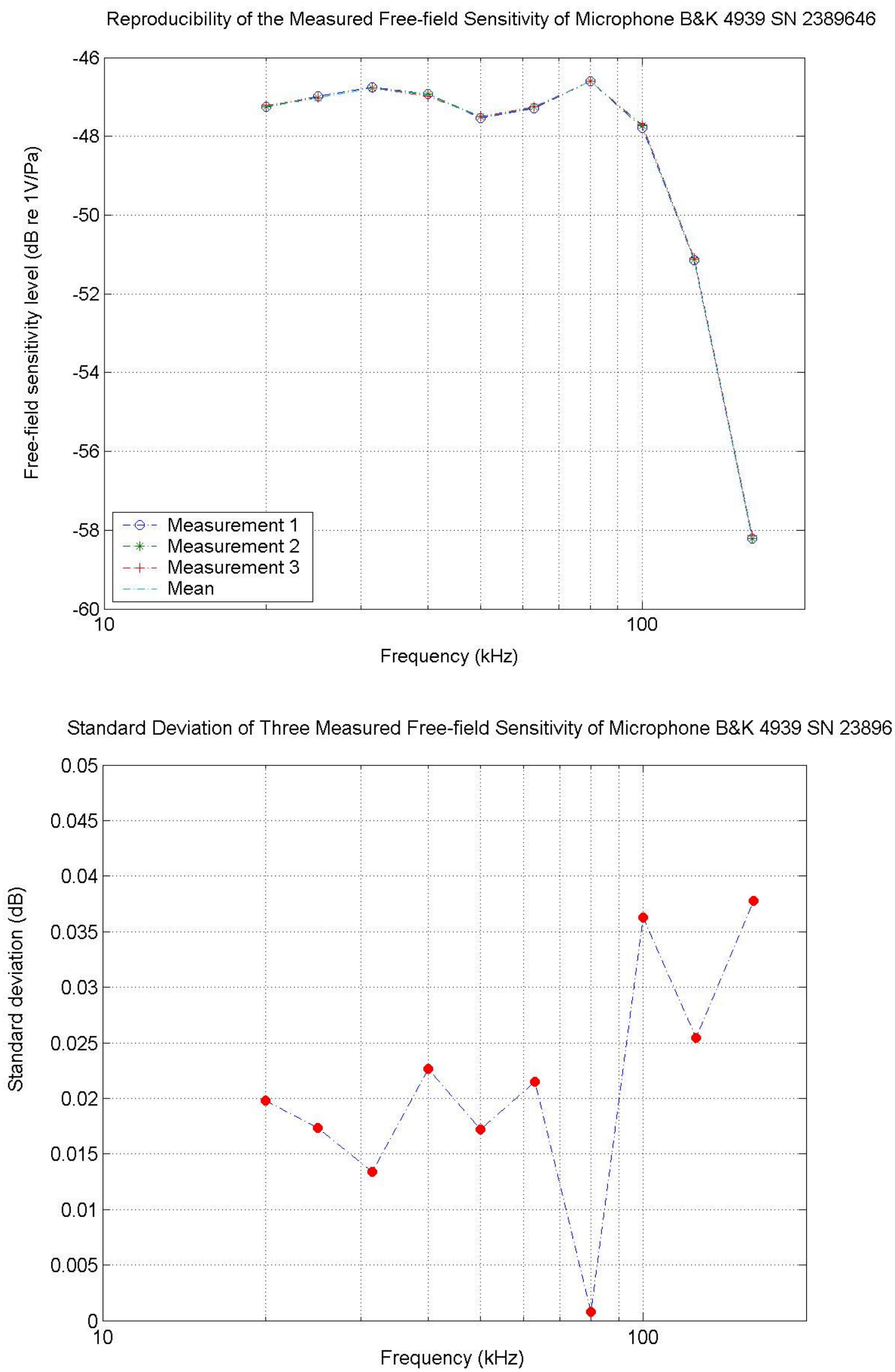


Figure III.21: Variation of the reproducibility of the measured free-field sensitivity of microphones B&K 4939 with frequency.

III.12 Free-field correction

The free-field reciprocity calibration is a complex and time-consuming method; one possibility permitting a rapid determination of the free-field sensitivity of condenser microphones is to use electrostatic calibration and add the free-field correction (the difference between free-field sensitivity and electrostatic actuator sensitivity). The electrostatic actuator method is rapid and inexpensive, but needs a known free-field correction and presents a significant uncertainty due to both uncertainties of free-field calibration and electrostatic actuator calibration.

This paragraph deals with the measurement of free-field corrections of ¼-inch condenser microphones B&K 4939. Figure III.22 shows the values of the free-field correction for condenser microphones of SN 2389646, 2389698 and 2389701. The free-field correction increases from about 4 dB at 20 kHz to approximately 9 dB at 50 kHz, and than decreases to approx. 5 dB at 125 kHz and increases to approx. 6.5 dB at 160 kHz. Table III.6 indicates the mean correction value of these three microphones, and its standard deviation, which is less than 0.25 dB, observed at 125 kHz.

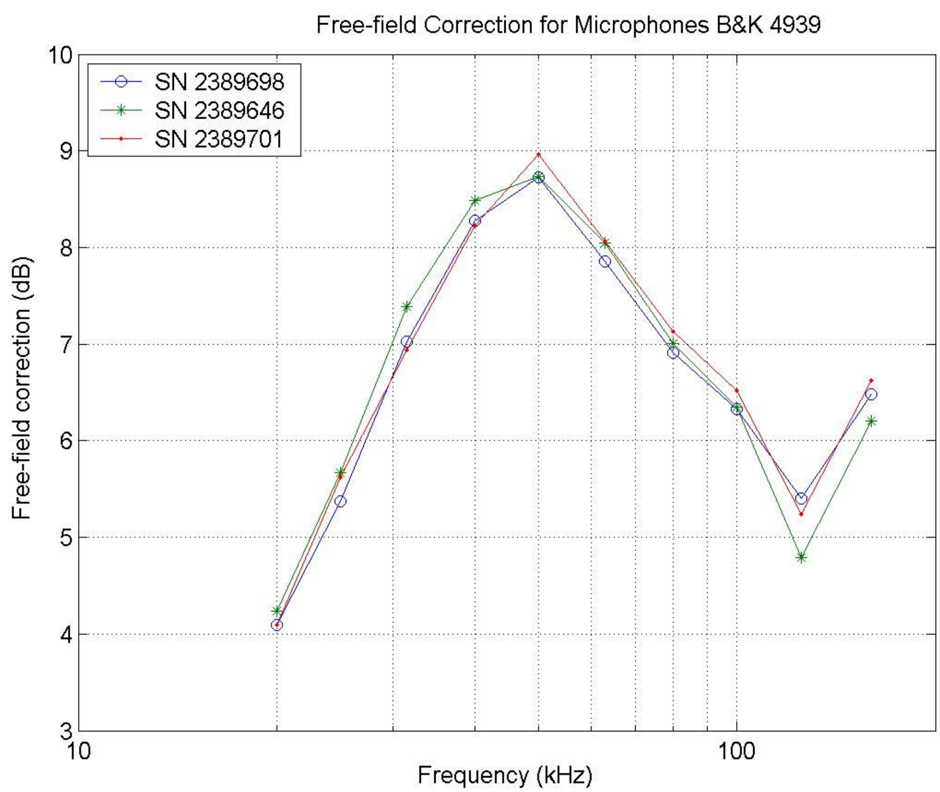


Figure III.22: Difference between the measured free-field sensitivity and electrostatic sensitivity as function of frequency.

Frequency (kHz)	Measured values of the free-field corrections for microphones B&K 4939 (dB)			Mean	Stdv.
	SN 2389698	SN 2389646	SN 2389701		
20	4.09	4.23	4.09	4.14	0.06
25	5.37	5.67	5.61	5.55	0.13
31.5	7.02	7.38	6.93	7.11	0.19
40	8.27	8.48	8.23	8.33	0.11
50	8.72	8.73	8.96	8.80	0.11
63	7.85	8.04	8.07	7.99	0.09
80	6.90	7.00	7.13	7.01	0.09
100	6.32	6.34	6.52	6.39	0.08
125	5.39	4.78	5.24	5.14	0.25
160	6.48	6.20	6.62	6.43	0.17

Table III.6: Measured values of the free-field corrections for microphones B&K 4939.

III.13 Conclusion

A new, automated set-up for the free-field reciprocity calibration of ¼-inch condenser microphones has been established. It allows the measurement of the free-field sensitivity of microphones in the ultrasonic frequency range from 20 kHz to 160 kHz. In order to make precise measurements, the effects of noise and crosstalk, standing waves, distortion of the driving voltage, acoustic center of the microphone, and of the environmental conditions have been carefully examined and optimized for the ultrasonic frequency range from 20 kHz to 160 kHz. The experimental results, the reproducibility of the free-field sensitivity of microphones B&K 4939 and the values of the free-field correction were indicated.

CHAPTER IV

UNCERTAINTY OF MEASUREMENT RESULTS

IV.1 Introduction

In the previous chapter, a new measurement set-up for the free-field reciprocity calibration of ¼-inch microphones in the frequency range from 20 kHz to 160 kHz was described, and the results of the calibration of three microphones B&K 4939 were given. In this chapter, the uncertainty of the measured free-field sensitivity is analyzed by using the free-field sensitivity expression and studying every possible component contributing to the uncertainty. An approach for the determination of the uncertainty of the free-field sensitivity is discussed; components of the measurement uncertainty are calculated following the GUM rules [GUM1993] with a model based on the free-field sensitivity formula.

IV.2 Uncertainty of the measured free-field sensitivity

The linear relative uncertainty u_x of a measurand x is defined as the difference δx between the measured and the true values relative to the true value, given by:

$$u_x = \frac{x_{measured} - x_{true}}{x_{true}} = \frac{\delta x}{x_{true}} \qquad \text{(IV.1)}$$

where
$x_{measured}$ is the measured value, and
x_{true} the true value.

The true value is approximated in the denominator to the measured value, thus

$$u_x = \frac{\delta x}{x_{measured}} \qquad \text{(IV.2)}$$

The uncertainty can also be expressed in the logarithmic scale; the logarithmic uncertainty is given by:

$$U_x = 20\log\frac{x_{measured}}{x_{true}} = 20\log\frac{x_{true} + \delta x}{x_{true}} = 20\log(1 + \frac{\delta x}{x_{true}}) = 20\log(1 + u_x) \qquad \text{(IV.3)}$$

When the measurand is a function of variables, the linear uncertainty is given by the root of the sums of the squares of the uncertainty of each variable:

$$u_x = (\sum_i u_i^2)^{1/2} \qquad \text{(IV.4)}$$

The logarithmic uncertainty is given by

$$U_x = 20\log(1 + (\sum_i u_i^2)^{1/2}) \qquad \text{(IV.5)}$$

The uncertainty of the measured free-field sensitivity is estimated from the uncertainties of the variables used for its calculation given in Eq. III.2 The combined standard uncertainty is the root of the sums of the squares of the standard uncertainty components [GUM1993], given by the formula:

$$\left(\frac{\delta M}{M}\right)^2 = \left(\frac{\delta M}{M}\right)^2_{\mathrm{Pol}} + \left(\frac{\delta M}{M}\right)^2_{\mathrm{St-Pr}} + \left(\frac{\delta M}{M}\right)^2_{\mathrm{Repr}} + \left(\frac{\delta f}{f}\right)^2 + \left(\frac{1}{4}\right)\left(\frac{\delta U_T}{U_T}\right)^2$$
$$+ \frac{3}{4}\left[\left(\frac{\delta U_R}{U_R}\right)^2 + \left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta d}{d}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\alpha d\frac{\delta \alpha}{\alpha}\right)^2 + \left(\alpha d\frac{\delta d}{d}\right)^2\right] \qquad \text{(IV.6)}$$

The uncertainty of each component was obtained by statistical methods, such as the repetition of the measurement (type A) or by other methods (called type B), e.g. on the basis of the certificate of an instrument. Uncertainty components are expressed as relative uncertainties and listed in table IV.1 in percent (%) for each frequency from 20 kHz to 160 kHz.

The abbreviation RSU means relative standard uncertainty

$\left(\frac{\delta M}{M}\right)_{Pol}$ **RSU due to the polarization**

The sensitivity of a microphone is directly proportional to the polarizing voltage (200 V DC); an error on the polarizing voltage will affect the measurement uncertainty. The measurement of the polarization was carried out by means of using a differential voltmeter (Fluke 805010) and showed a maximum deviation of 50 mV for the transmitter microphone and 120 mV for the polarization of the receiver microphone.

$\left(\frac{\delta C}{C}\right)$ **RSU of the measured capacitance**

The uncertainty of the measured capacitance was 0.05% based on the certificate the capacitance bridge (type 7600 Precision RLC Meter).

$\left(\frac{\delta M}{M}\right)_{\mathrm{Repr}}$ **RSU due to the reproducibility of measurements**

The standard deviation of the measured sensitivity for three measurements is less than 0.04 dB for the whole frequency range.

$\left(\frac{\delta f}{f}\right)_{Pol}$ **RSU due to the frequency**

The uncertainty of the frequency of the generated signal was 100 PPM based on the certificate of the Frequency Response Analyzer SOLARTRON.

$\left(\frac{\delta \mathrm{U_T}}{\mathrm{U_T}}\right)$ **RSU of the driving voltage**

The uncertainty of the driving voltage was 0.02 dB based on certificate of the Frequency Response Analyzer SOLARTRON.

$\left(\frac{\delta U_R}{U_R}\right)$ **RSU of the receiver voltage:**

The uncertainty of the open-circuit voltage of the receiver microphone results from an acoustic interference (standing waves and reflections), or from an electrical interference (crosstalk). In order to minimize the uncertainty, special care to the instrumentation has been taken during the realization of the set-up. Crosstalk occurs at lower frequencies (below 40 kHz), where the signal-to-crosstalk ratio is low. Thus, a distance range from 10 cm to 20 cm has been chosen (the signal-to-crosstalk ratio decreases with increasing distance). At higher frequencies (above 80 kHz) the effects of standing waves are dominant; a larger distance range (20 cm to 30 cm) is therefore used for measurements to minimize these effects. The standard uncertainty of the receiver voltage (type A) is calculated as standard deviation from the linear interpolation over the distance of the inverse of the open circuit voltage corrected for the attenuation of air.

$\left(\frac{\delta d}{d}\right)$ **RSU of the measurement distance**

The effective distance between the microphones is deduced from the physical distance measured between the two microphone diaphragms and the acoustic center, calculated from the linear interpolation of the open-circuit voltage corrected for attenuation as a function of distance. The maximum standard uncertainty of the distance is estimated to be 0.5 mm.

$\left(\frac{\delta\rho}{\rho}\right)$ **RSU of the density**

According to [Wong 1995] the uncertainty of the calculated density is less than 130 PPM.

$\left(\frac{\delta M}{M}\right)$ **Combined relative uncertainty of the free field sensitivity:**

The combined relative uncertainty was obtained by using Eq. (IV.6). The expanded uncertainty was calculated as:

$$(\delta M/M)_{Exp} = k(\delta M/M)$$

where *k* is the coverage factor. For *k* = 2 (confidence level 95%), the expanded uncertainty is according to table IV.1, less than 0.2 dB in the frequency range from 20 kHz to 160 kHz.

Comp-onent	Type	Distribu-tion	Standard uncertainty contribution of	Standard uncertainty in % at frequency (kHz)									
				20	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
$\left(\frac{\delta U_R}{U_R}\right)$	A	normal	Receiver voltage due to crosstalk and standing waves	0.25	0.22	0.13	0.17	0.17	0.28	0.18	0.15	0.13	0.46
	B	rectangular	Receiver voltage due the analyzer	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$\left(\frac{\delta U_T}{U_T}\right)$	B	rectangular	Driving voltage	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$\left(\frac{\delta C}{C}\right)$	B	rectangular	Capacitance	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
$\left(\frac{\delta d}{d}\right)$	B	rectangular	Distance	0.35	0.35	0.35	0.35	0.25	0.25	0.20	0.20	0.20	0.20
$\left(\alpha d\frac{\delta\alpha}{\alpha}\right)$	B	rectangular	Absorption	0.06	0.07	0.09	0.11	0.18	0.22	0.35	0.45	0.60	0.86
$\left(\frac{\delta M}{M}\right)_{Pol}$	B	rectangular	Polarization voltage	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
$\left(\frac{\delta M}{M}\right)_{S\text{–}\mathrm{Pr}}$	B	rectangular	Static pressure dependency	0.00	0.03	0.09	0.18	0.26	0.28	0.32	0.36	0.18	0.06
$\left(\frac{\delta M}{M}\right)_{\mathrm{Re}p}$	A	normal	Reproducibility	0.10	0.18	0.14	0.21	0.13	0.09	0.22	0.40	0.07	0.29
$\left(\frac{\delta M}{M}\right)$			Combined uncertainty of sensitivity	0.53	0.42	0.39	0.46	0.46	0.51	0.58	0.73	0.62	0.93
$\left(\frac{\delta M}{M}\right)_{Exp}$			Expanded uncertainty of sensitivity in %, (k=2 , confidence level 95 %)	1.07	0.85	0.79	0.93	0.93	1.03	1.17	1.46	1.25	1.87

Table IV.1: Uncertainty of free-field sensitivity for microphones B&K 4939. The values shown are in percent for frequencies from 20 to 160 kHz.

CHAPTER V

INVESTIGATIONS ON A TIME-SELECTIVE TECHNIQUE FOR THE CALIBRATION OF MICROPHONES

V.1 Introduction

One of the problems in implementing the set-up for the free-field reciprocity calibration of condenser microphones is the realization of the free-field conditions, which could be affected by a non-ideal performance of the anechoic room resulting in disturbing reflections from the walls. Furthermore the interaction between the two microphones coupled in the free field causes standing waves and crosstalk. These disturbances can have a significant influence on the measured free-field sensitivity. They can be eliminated in the time domain by means of a time-selective window applied to the impulse response of the microphone.
The use of a time-selective technique permitting the identification of disturbances due to crosstalk, standing waves and reflections and the possibility of their elimination is described.

V.2 Time-selective technique

The free-field reciprocity calibration of condenser microphones is based on the measurement of the electrical transfer function (ETF) between two microphones coupled under free-field conditions, defined as the ratio of the open circuit voltage of the receiver microphone U_2 to the driving voltage the transmitter microphone U_1

$$ETF_{12} = \frac{U_2}{U_1} = i\,\frac{\rho f}{2d} M_1 M_2 e^{i\alpha d}$$

The imperfections in the ETF (due to reflections, standing waves, and crosstalk) can be eliminated from the ETF using an FFT-based time-selective technique. The impulse response of the ETF can be calculated by applying the inverse Fourier transform (IFT) to the measured ETF which contains the direct wave between the microphones and the disturbances (reflections, standing waves and crosstalk). These disturbances can be eliminated by means of a time window, and then the cleaned Electrical Transfer Function ETFC can be calculated by applying the Fourier transform to the windowed impulse response (IRW).

$$\mathrm{EFT}(f) \xrightarrow{\mathrm{IFT}} \mathrm{IR}(t) \xrightarrow{\mathrm{W}(t)} \mathrm{IRW}(t) \xrightarrow{\mathrm{FT}} \mathrm{ETFC}(f)$$

V.3 Investigations on a time-selective technique for the calibration of ¼-inch microphones

V.3.1 ETF and Impulse response

The procedure proposed for identifying the disturbances in the Electrical Transfer Function, is based on the measurement of the ETF step by step with pure tones of increasing frequency in a finite frequency range. Then the missing frequency portions of the ETF are completed by an adequate procedure [Barrera2003]. Finally, the impulse response function is obtained by applying the Inverse Fourier Transform to the completed ETF.

Due to the poor signal-to-noise ratio at lower frequencies the ETF is only measured above the lower frequency limit f_{min}. The sensitivity of the condenser microphone decreases at high frequencies (above the resonance frequency) and tends to zero asymptotically, and so does so the ETF.

The ETF is only measured in a limited frequency range [f_{min} f_{max}], but for the application of inverse Fourier transform knowledge of the ETF in the whole frequency domain is needed. The lower frequency range [0 f_{min}] and the higher frequency range [f_{max} $+\infty$] must be generated and added [Barrera2003].

The missing low frequency values of the ETF can be generated by extrapolating the measured ETF in the frequency range [0 f_{min}]. The missing high frequency part of the ETF can be handled by using a low-pass filter, of a value of unity in the interval [0 f_{max}] and zero in the in the interval [f_{max} $+\infty$].

The complex ETF was measured for a pair of ¼-inch condenser microphones B&K 4939 facing each other with a separation of 10 cm,in the frequency range from 5 kHz to 150 kHz in 100 Hz frequency steps (see figure V.1-a).

Figure V.1-b shows the ETF extended to lower frequencies and low-pass filtered.

After that, an inverse Fourier transform was applied to the completed ETF. The obtained normalized impulse response is shown in figure V.2.

In this case the expected direct wave coming from the transmitter microphone will arrive to the transmitter microphone at $t_{\mathrm{DW}}= d/c$ (t_{DW}=0.29 ms, d=0.1 m and c=345.8 m/s), as can be seen in figure V.2.

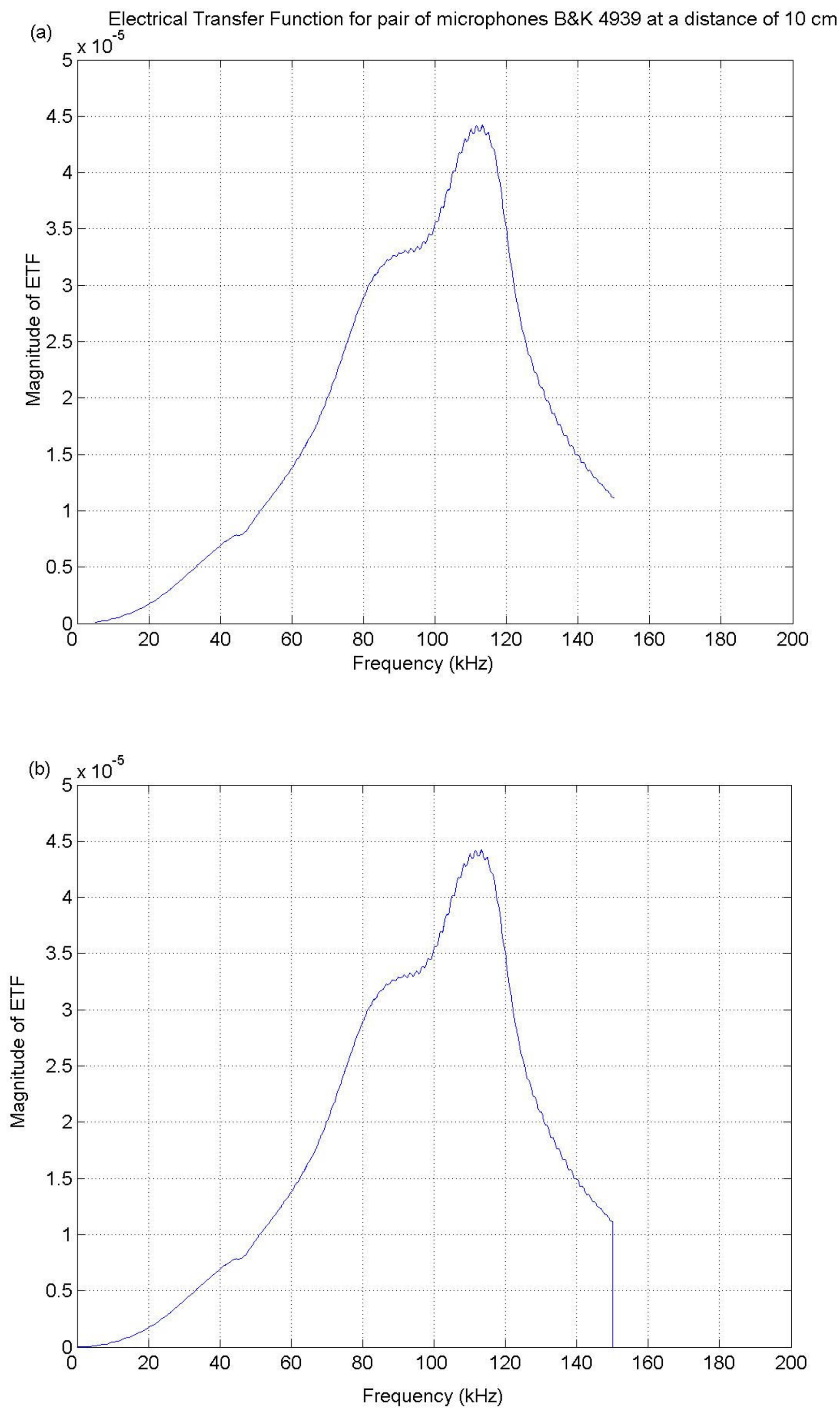


Figure V.1: Magnitude of the electrical transfer function between two ¼-inch condenser microphones B&K 4939 located at 10 cm. a) measured, b) extended and low pass filtered.

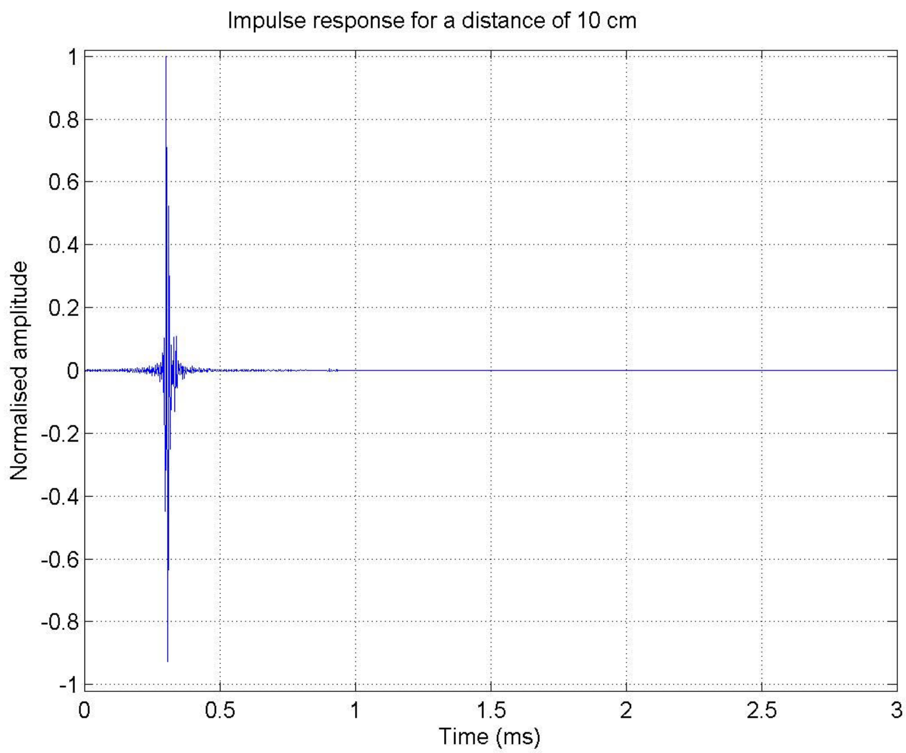


Figure V.2: Normalized impulse response of the electrical transfer function between two ¼-inch condenser microphones B&K 4939 located at 10 cm.

V.3.2 Disturbance in the ETF

Standing wave disturbance is more pronounced for small distances between the transmitter and receiver microphones and for higher frequencies (figure V.3) and results in an oscillation with a frequency interval $\delta f = c/2d$ (see paragraph II.7.2). For a distance of 10 cm an oscillation with a frequency interval of 1.7 kHz (c=345 m/s) is observed (figure V.4-a)
Crosstalk disturbance is more pronounced for higher distances between the transmitter and receiver microphones, at lower frequencies and results in an oscillation with a frequency interval δ f = c/d (see paragraph II.7.2). For a distance of 20 cm an oscillation with a frequency interval of 1.7 kHz is observed (figure V.4b).

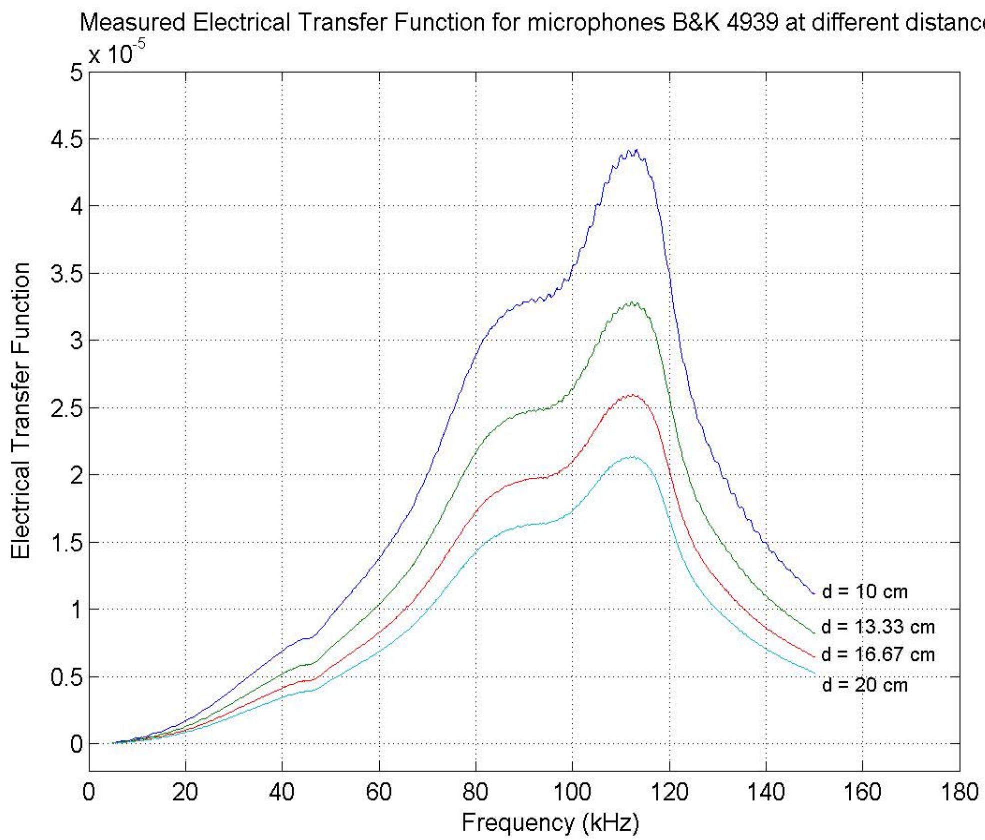


Figure V.3: Magnitude of the electrical transfer function measured at several distances between the microphones (10 cm, 13.33 cm, 16.67 cm and 20 cm).

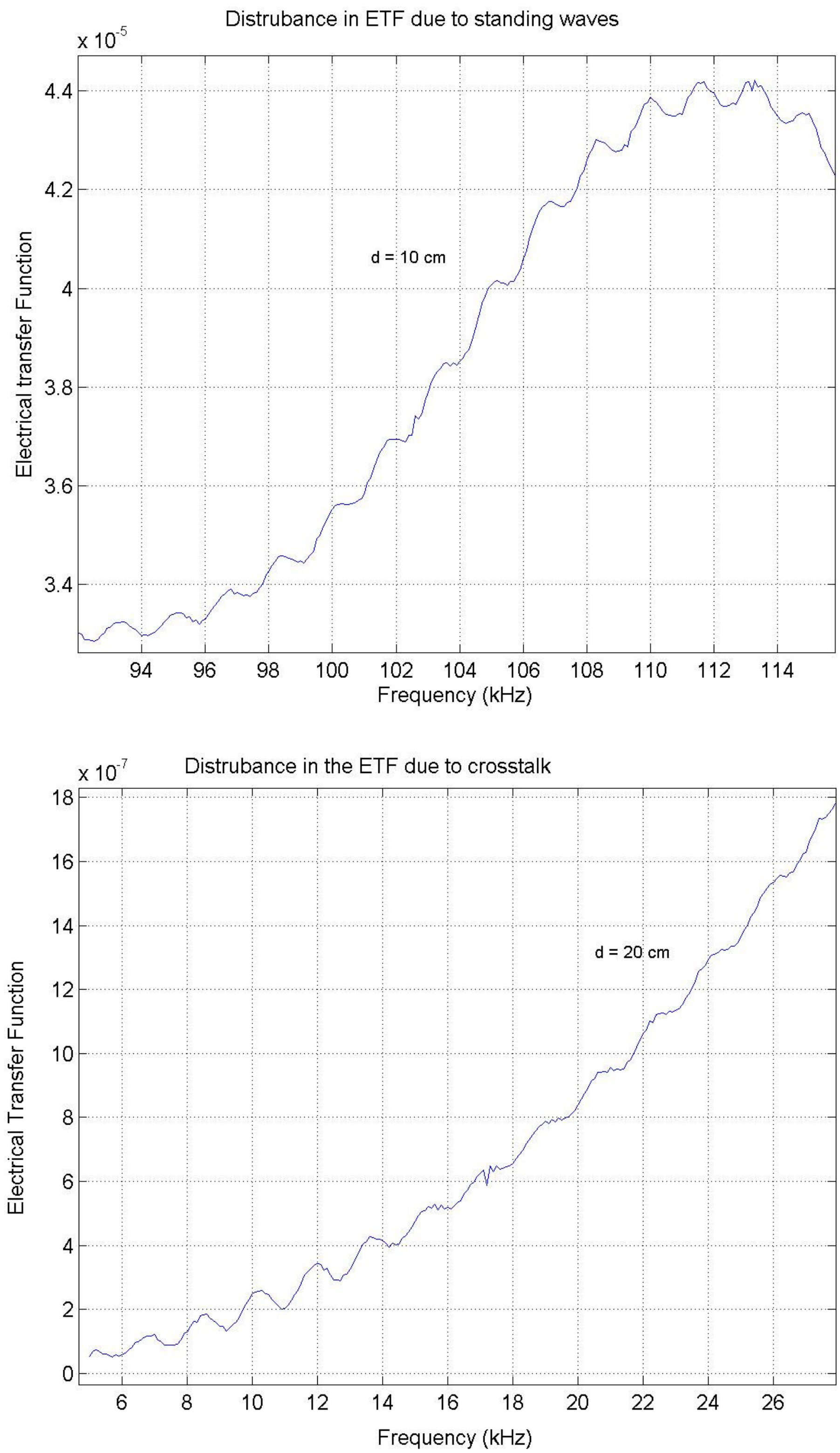


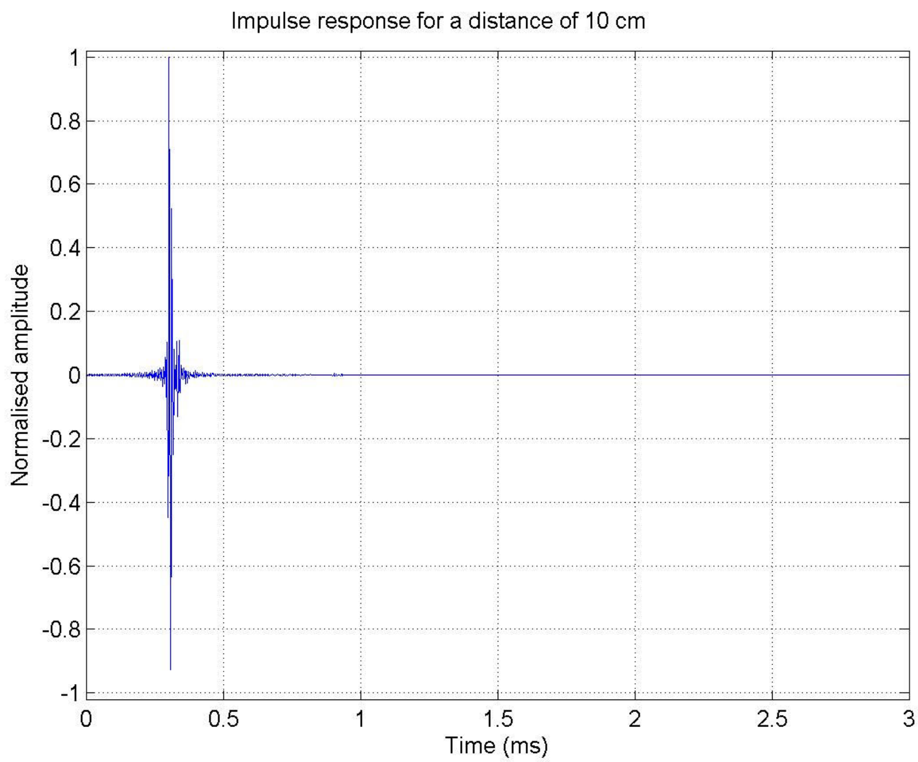
Figure V.4: Zoom on the graph of the measured electrical transfer function to show the disturbances due to crosstalk and standing waves. a) Disturbance of the ETF measured at a distance of 10 cm, due to standing waves, b) Disturbance in the ETF measured at a distance of 20 cm, due to crosstalk.

V.3.3 Disturbance in the impulse response

The impulse response of the ETF contains the direct propagating wave between the microphones, crosstalk and standing waves. Each component can be determined according to its time of arrival. Due to its electrical origin crosstalk will arrive at time zero before the direct wave. A standing wave travels three times the distance between the microphones, so it will occur after the direct wave at three times the arrival time of the direct wave.

In figures V.5-8 it is possible to see the disturbance by crosstalk which appears at t=0 and then the direct wave and the disturbance by standing waves which appears at three times the time of the direct wave, for each distance.

a)



b)

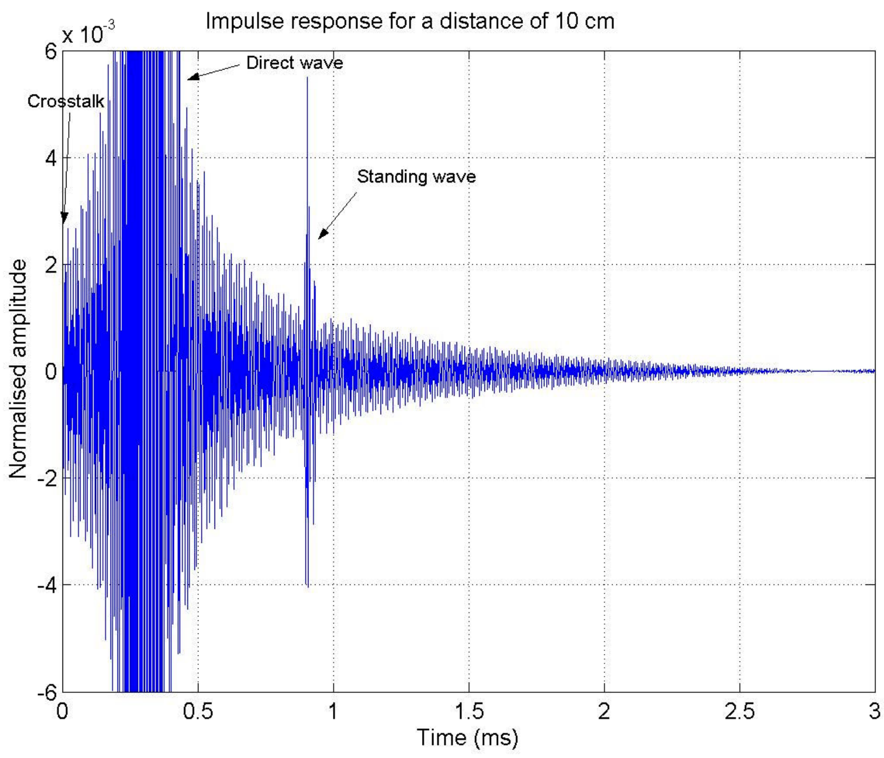
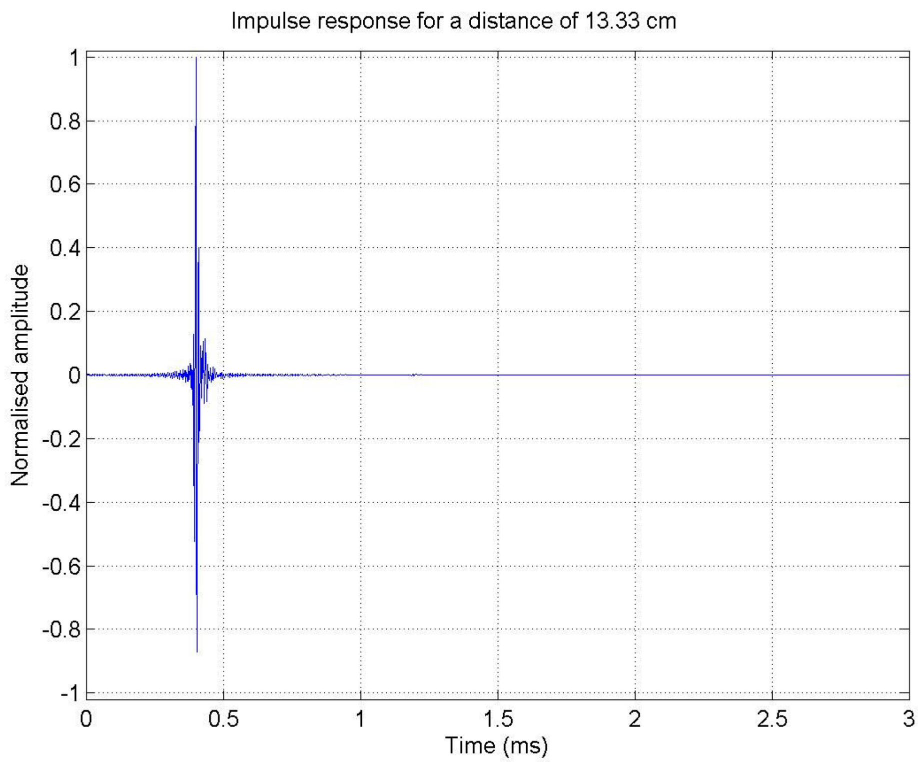


Figure V.5: a) Normalized impulse response of the electrical transfer function between two ¼-inch condenser microphones B&K 493, distance of 10 cm. b) Zoom on graph of the normalized impulse response to show the components: crosstalk, direct wave and standing wave.

a)



b)

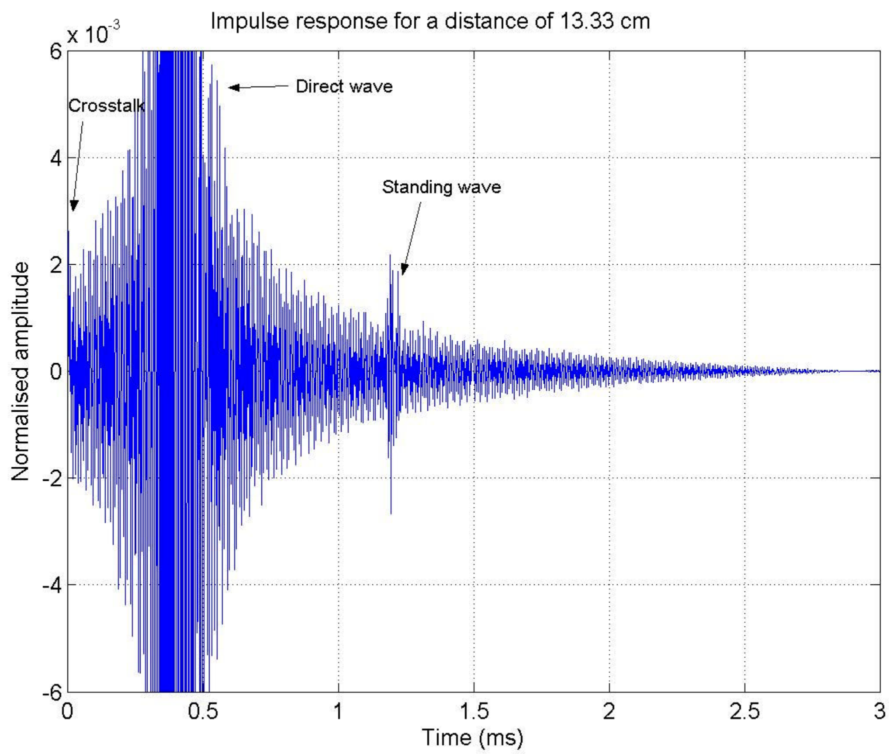


Figure V.6: a) Normalized impulse response of the electrical transfer function between two ¼-inch condenser microphones B&K 4939, distance of 13.33 cm. b) Zoom on the graph of the normalized impulse response to show the components: crosstalk, direct wave and standing wave.

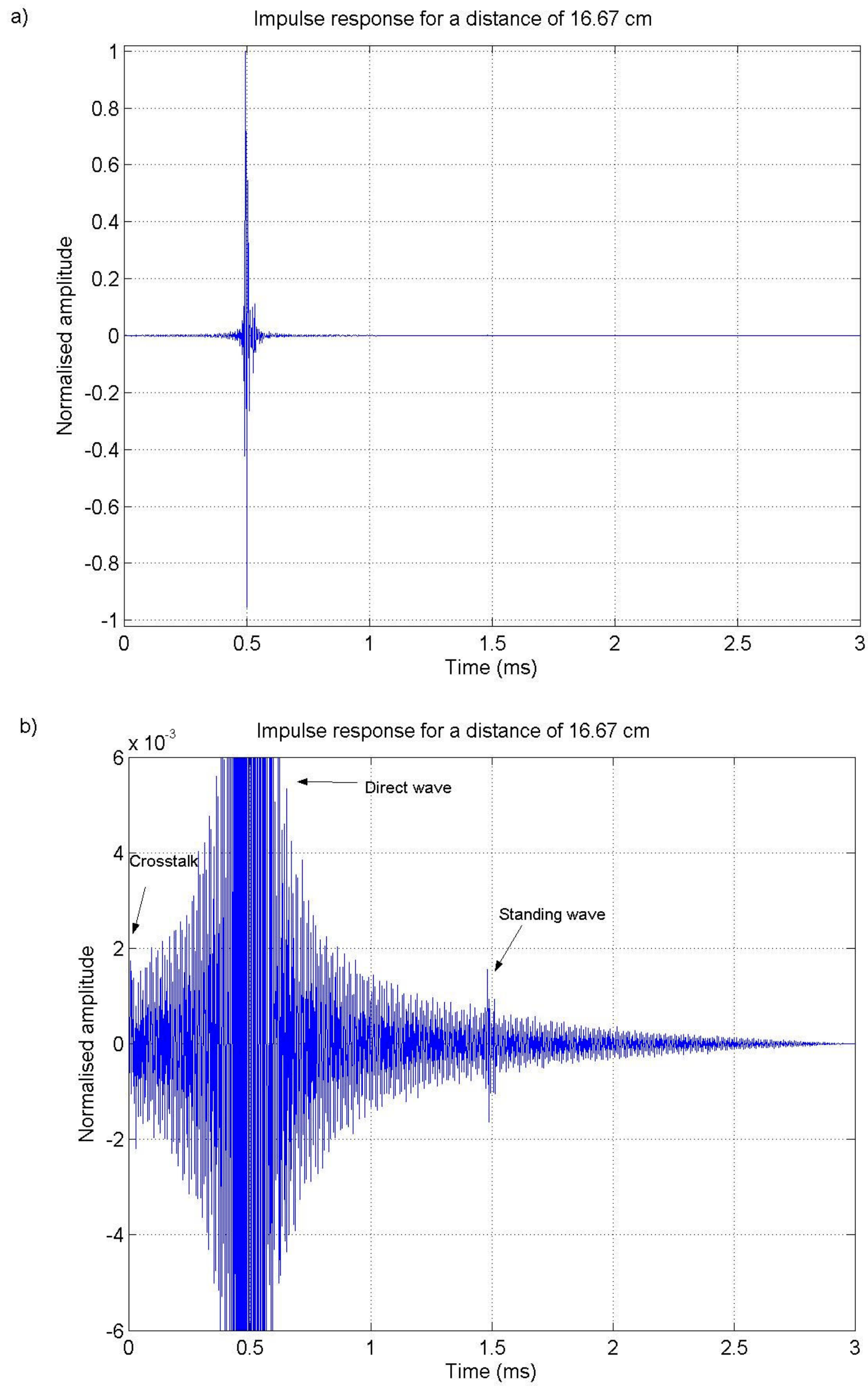
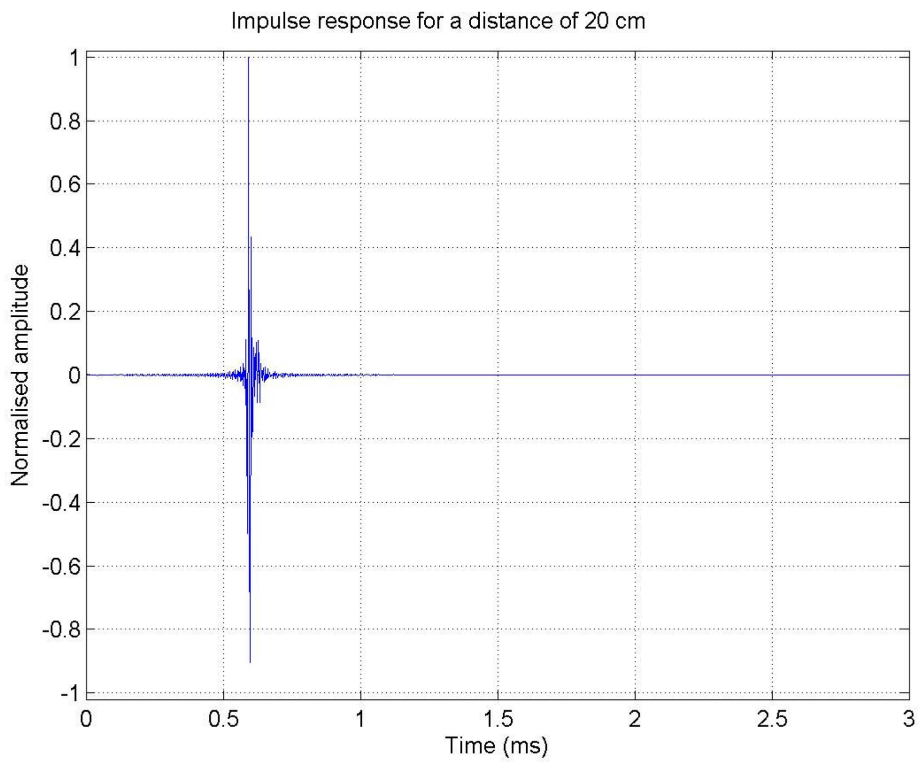


Figure V.7: a) Normalized impulse response of the electrical transfer function between two ¼-inch condenser microphones B&K 4939, distance of 16.67 cm. b) Zoom on the graph of the normalized impulse response to show the components: crosstalk, direct wave and standing wave.

a)



b)

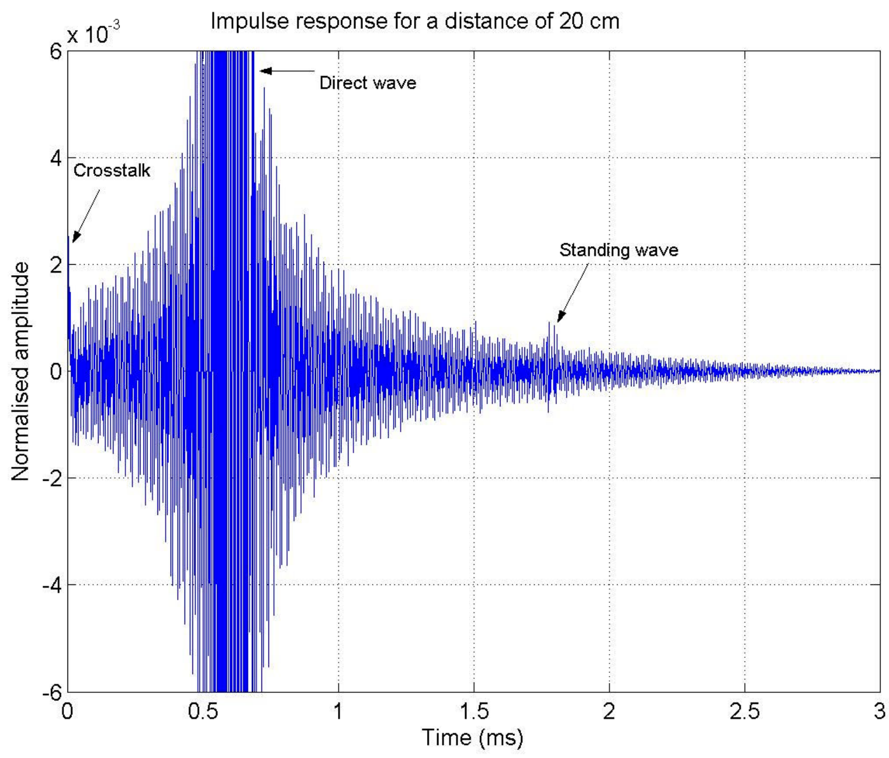


Figure V.8: a) Normalized impulse response of the electrical transfer function between two ¼-inch condenser microphones B&K 4939, distance of 20 cm. b) Zoom on the graph of the normalized impulse response to show the components: crosstalk, direct wave and standing wave.

A time-selective window can be applied to the impulse response in order to eliminate the disturbances and to keep only the direct wave of the ETF. The cleaned ETF can then be obtained by applying the Fourier Transform to the time-windowed ETF (figure V.9).

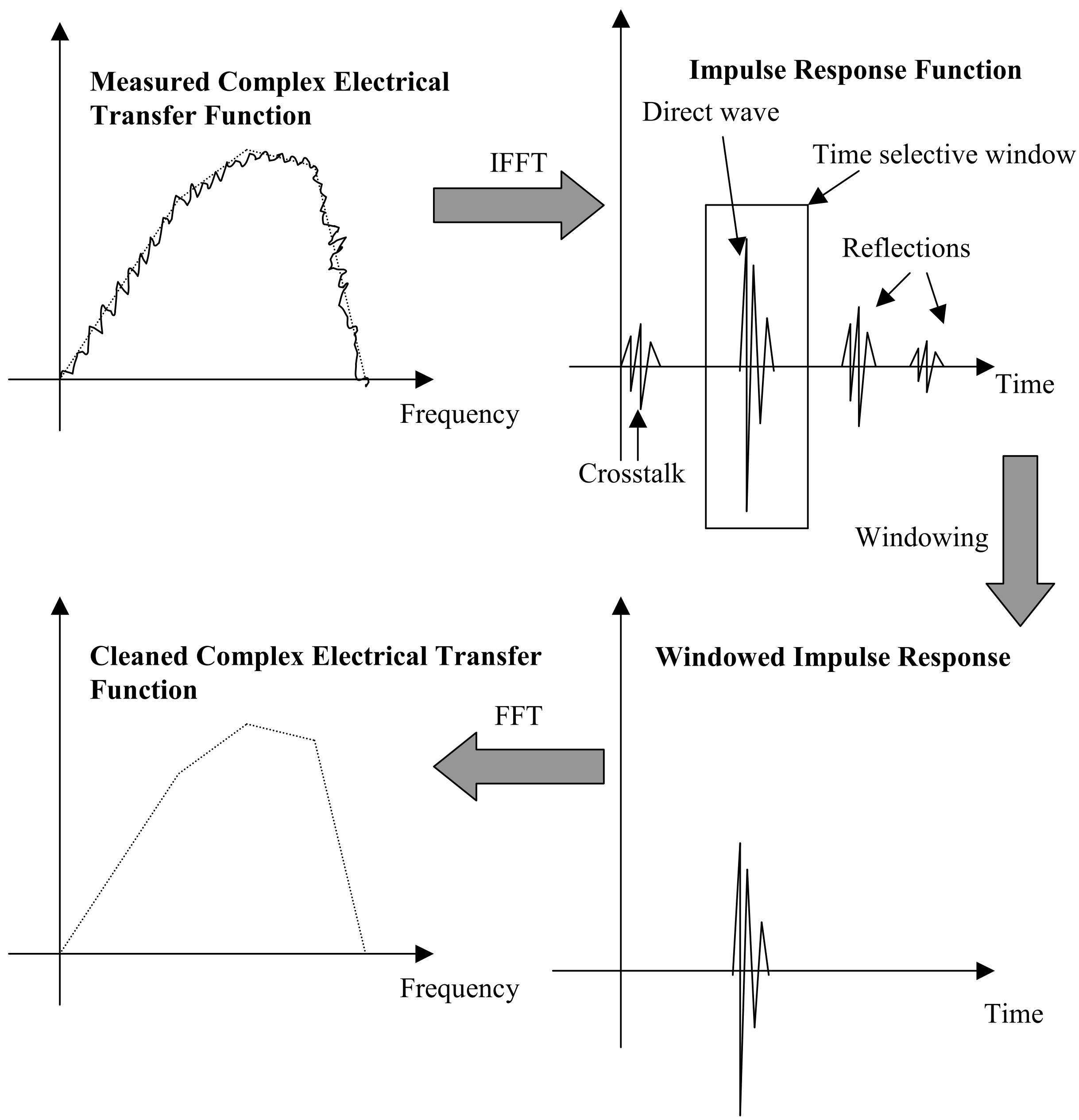


Figure V.9: Schematic diagram of the procedure for the removal of the disturbances of a complex electrical transfer function between two microphones.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

CONCLUSIONS AND FUTURE WORK

VI.1 Conclusions

The precise calibration of condenser microphone plays a fundamental role in acoustic measurements and has been limited to the audible frequency range for a long time. The increasing use of ultrasound in several technical and medical applications and in our daily life was the reason for extending the frequency of the calibration of condenser microphones to the low ultrasonic frequency range.

The basic aim of the thesis work described in this report was the realization of the primary standard of sound pressure in the low ultrasonic frequency range in terms of the sensitivity of ¼-inch microphones calibrated by the reciprocity method under free-field conditions.

A new automated measurement set-up for the free-field reciprocity calibration of condenser microphones has been established at PTB [Bouaoua2004] [Bouaoua2005] [Bouaoua2006]. First, a new preamplifier having the diameter of ¼-inch condenser microphones was designed and manufactured to allow the measurement of the open-circuit voltage of ¼-inch condenser microphones when used as receiver microphones. The free-field performance of the anechoic room was then tested in the ultrasonic frequency range from 20 kHz to 160 kHz, by analyzing the deviation of the measured sound pressure of the receiver microphone as function of distance between the transmitter and receiver microphones from the inverse distance low. The results of this test showed a good free-field performance of the anechoic room and the deviation from the ideal free-field behavior over this frequency range (less than 0.1 dB) was due to the interaction between the transmitter and receiver microphones (crosstalk and standing waves).

During the development of the measurement set-up, crosstalk was one of the major practical problems to be solved because of the low output voltage of the ¼-inch condenser microphones. The identification and the evaluation of the level of crosstalk were performed in two ways: by scanning the acoustic field as function of distance, and determining the deviation from the inverse distance law. The second method uses a measuring capacitance having the same capacitance as the transmitter microphone, used as a transmitter; this allows a direct evaluation of the crosstalk. For the optimization of the measurement set-up, several steps were taken progressively to minimize the level of crosstalk, and control the level of crosstalk so that an uncertainty due to crosstalk of less than 0.1 dB could be achieved. A driving voltage of the transmitter microphone of 3 V was chosen as a compromise for low distortion and good signal-to-noise ratio of the output voltage of the receiver microphone.

After optimizing all parameters, the reciprocity method was implemented by using three microphones in three pairs, where each is used as both transmitter and receiver. The free-field sensitivity of ¼- inch condenser microphones B&K 4939 was measured in the ultrasonic frequency range from 20 kHz to 160 kHz, taking into account the acoustic center and static pressure correction of the condenser microphone. By subtracting the electrostatic actuator sensitivity from the free-field sensitivity for the three microphones, the free-field correction for this type of microphones was obtained.

The components of the measurement uncertainty were calculated following the GUM rules with a model based on the free-field sensitivity formula, and are given in the ultrasonic frequency range 20 kHz to 160 kHz. The uncertainty of the measured free-field sensitivity is estimated to be less than 0.2 dB.

The end of this thesis investigated the use of a time-selective technique permitting the identification of disturbances due to crosstalk, standing waves and the possibility for the removal of these disturbances in the time domain.
The procedure proposed for identifying these disturbances in the Electrical Transfer Function, is based on the measurement of the ETF step by step with pure tones of increasing frequency at a given distance between the transmitter and receiver microphones. The impulse response was then obtained by applying the inverse Fourier transform to the measured complex ETF. The characteristics of these disturbances (crosstalk and standing wave) were described and discussed. The possibility of eliminating these disturbances in the time domain was proved and will be the next work in the future.

VI.2 Future work

- Improve the time-selective technique: by applying a time window to the impulse response in order to eliminate the disturbances, and studying the effects of the windowing on the real impulse response by using numerical simulations.

- Make an inter-comparison with other national metrology institutes.

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbständig verfasst habe und nur die angegebenen Hilfsmittel benutzt habe.

Oldenburg, 16 March 2008

Nourreddine Bouaoua

CONFERENCE PAPERS

N. Bouaoua, T. Fedtke and V. Mellert "Uncertainty in the realization of the standard of sound pressure in low ultrasonic frequency range by the free-field reciprocity technique", Proceedings of 32. Deutsche Jahrestagung für Akustik (DAGA'06), Braunschweig-Germany, March 2006, pp. 115-116.

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CURRICULUM VITAE

I – Personal Information

Nourreddine BOUAOUA
Born on December 15, 1975 in Algiers, Algeria:
Citizen of Algeria
Married (two children)

II – Education

1981-1987	Primary school in Algiers, Algeria.
1987-1990	Collège d'Enseignement Moyen in Algiers, Algeria
1990-1993	Secondary school, Lycée Benrahal in Algiers, Algeria
06/1993	Baccalauréat de l'Enseignement Secondaire
1993–1998	High Diploma in Physics, option Materials and Components (Diplôme d'Etudes Supérieures en Physique, option: Matériaux et Composants), Institute of Physics, University of Sciences and Technology Houari Boumédiène (U.S.T.H.B.), Algiers, Algeria
1998–2002	Master in Physics (Magister en Physique), Institute of Physics, University of Sciences and Technology Houari Boumédiène (U.S.T.H.B.), Algiers, Algeria.
	12/1998-12/1999 Theoretical courses
	12/1999-06/2002 Preparation of a Magister thesis in Ultrasound Physics, entitled: "Contribution to the study of the radiation and the diffraction of transient ultrasonic fields in viscous media"
10/2002	Master diploma in Physics.
2003-2006	Ph.D. Student in Physics at the Institute of Physics, University of Oldenburg

III- Professional experience

1998-2000	Assistant Lecturer of physics at the University of Boumerdes (Algeria)
2003-2006	Research Assistant at the Acoustics Laboratory of the Physikalisch-Technische Bundesanstalt (PTB)
04/2007	Physicist at ROSEN Technology & Research Center

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