Measurement system for reciprocity calibration

Master's thesis in Sound and Vibration

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Department of Civil and Environmental Engineering
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Abstract

This master's thesis is a collaboration between SP (Technical Research Institute of Sweden) and Chalmers University of Technology. The project consisted of developing a reciprocity calibration system for 1/2-inch and 1-inch laboratory standard microphones. Calibration by reciprocity is one of the most accurate techniques to calibrate primary standard condenser microphones. The work included implementing code from a previous system into LabVIEW as well as updating the theory according to new standards and setting up new hardware for the calibration system.

Comparisons of results from different calibration systems indicate that the newly developed calibration system gives results that are more accurate than the previously used system, especially at high frequencies. An international key comparison for calibration of 1-inch laboratory standard microphones will give a definitive answer on the precision of the system.

Acknowledgements

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Introduction

The method of calibration by reciprocity is used to acquire the absolute sensitivity of a set of three microphones. These microphones need to be reciprocal transducers, i.e. condenser microphones which can work either as a receiver or transmitter of sound with equal ratio of response to excitation for the two operation modes [1].

The microphones are coupled pair-wise through a gas enclosed in a cavity. An input current is connected to the transmitter transducer, making it emit sound into the cavity. The receiver transducer detects the sound and produces an output voltage. The electrical transfer impedance, i.e. the ratio between the output voltage and the input current, is acquired for each pair of transducers. By repeating this measurement for all combinations of three microphones the pressure sensitivity levels of the microphones can be acquired.

An international key comparison is taking place between 2013 and 2015, in which the pressure sensitivity level of two 1-inch laboratory standard microphones of type B&K 4160 are calibrated according to International Standard IEC 61094-2 [2]. In preparation of this key comparison the reciprocity calibration system at SP (Technical Research Institute of Sweden) was to be updated both with respect to hardware and software. There was also some theory upon which the calculations were based that was outdated and in need of refinement.

The aim of the project was to develop a calibration system with hardware updates from the previous system and written in LabVIEW-code. Updated theory was to be implemented in the code, to give better accuracy of the results in certain frequency ranges. The calibration system was to be constructed for two-channel measurements and to use frequency response function to measure the voltage ratios, thus reducing the calibration time from the previous calibration system. It was then to be evaluated, by comparison to previous calibration results, whether the new calibration system could provide accurate results.

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Theory

2.1 Microphones

A condenser microphone is a microphone that operates by variation of electrical capacitance [3]. The condenser microphone types mainly used in reciprocity calibration are the 1/2-inch laboratory standard microphone of the type B&K 4180 as well as the 1-inch laboratory standard microphone of type B&K 4160. However it is desired for the system to be able to handle also other types of laboratory standard microphones, such as the B&K 4134 1/2-inch microphone and the B&K 4144 1-inch microphone. The microphones require a polarization voltage of 200 V.

Microphone parameters of interest when conducting calibration by reciprocity are the acoustic compliance, acoustic mass and acoustic resistance as well as the characteristics of the front cavity of the microphone, which is the cavity between the front surface of the microphone and the diaphragm. The front cavities of the microphones in a reciprocity calibration measurement gives a contribution to the surface area and volume of the cavity between the microphones. The characteristics of the front cavity is for this reason divided into the front volume and the depth of the microphone.

2.2 Coupler type

When conducting a microphone calibration by reciprocity the cavity between the microphones could be either a plane-wave coupler or a large-volume coupler. A plane-wave coupler has the same diameter as the microphone diaphragm, while a large-volume coupler has a volume that far exceeds the sum of the equivalent volumes and front volumes of the microphones. The large-volume coupler will give less influence from the equivalent volumes of the microphones, but has the drawback that the results will only be viable at lower frequencies, as the maximum dimensions of the cavity should not exceed $\lambda/20$ [4].

The plane-wave coupler can be seen as an ideal acoustic transmission line, which gives a wide frequency range of validity. The plane-wave coupler will however be more sensitive to heat conduction between the enclosed gas and the surface of the cavity, due to a higher ratio between surface area and volume [5]. The plane-wave coupler will also be more sensitive to errors in the equivalent volume and impedance of the microphones. To minimize these errors calibration can be made with several different couplers followed by a data fitting method for the microphone parameters. This data fitting is based on the assumption that the calibration result should be independent of the dimensions of the applied plane-wave coupler.

This report treats the plane-wave coupler type, which is the primarily used type of coupler in modern reciprocity calibration systems.

2.3 Pressure sensitivity

For a cavity with a pair of condenser microphones the acoustical impedance, $Z_{a,AB}$, is given by equation (2.1), where κ_r is the ratio of specific heats of the gas in the cavity at reference temperature, given as 1.40 [3]. $P_{s,r}$ is the reference value of the barometric pressure in the cavity, given as 101.325 kPa. ω is the angular frequency of the driving signal and $V_{a,AB}$ is the acoustic volume of the coupler including the equivalent volume of the microphones, given by equation (2.14).

$$Z_{a,AB} = \frac{\kappa_r P_{s,r}}{j\omega V_{a,AB}} \tag{2.1}$$

The known expression of the impedance given in equation (2.2) is also of interest. Here p is the pressure in the cavity and u is the volume velocity in the cavity.

$$Z_{a,AB} = \frac{p}{u} \tag{2.2}$$

According to the reciprocity theorem, the ratio between the volume velocity, u, at the diaphragm in the cavity and the input current, I, when a passive reversible reciprocal transducer is used as a source is equal to the ratio between the open-circuit voltage, e, and the sound pressure, p, acting on the diphragm when the same transducer is used as a receiver, see equation (2.3) [4]. This ratio is the sensitivity of the transducer.

$$M_A = \frac{u}{I_A} = \frac{e_A}{p} \tag{2.3}$$

Expressing the input current in terms of an input voltage with an electrical impedance, Z_x, see equation (2.4), the sensitivites of a pair of microphones in the setup can be expressed as in equation (2.5). Here M_A is the sensitivity of the transmitter transducer and M_B is the sensitivity of the receiver transducer [4].

$$I_A = \frac{e_A}{Z_x} \tag{2.4}$$

$$M_A M_B = \frac{e_B}{e_A} \frac{j\omega Z_x V_{a,AB}}{\kappa P_s} \tag{2.5}$$

This relationship holds equally for all combinations of the transducers, so to acquire three equations to be able to solve the sensitivity of the transducers equations (2.6) and (2.7) are also used.

$$M_B M_C = \frac{e_C}{e_B} \frac{j\omega Z_x V_{a,BC}}{\kappa P_s} \tag{2.6}$$

$$M_C M_A = \frac{e_A}{e_C} \frac{j\omega Z_x V_{a,CA}}{\kappa P_s} \tag{2.7}$$

To make the expression more comprehensible a variable, k, is introduced, given by equation (2.8). Similarily, an expression for the ratio between input voltage and output voltage is given in equation (2.9). This, divided by a calibration voltage ratio, can be seen as the electrical transfer impedance of the system.

$$k = \frac{j\omega Z_x}{\kappa P_s} \tag{2.8}$$

$$\beta_{AB} = \frac{e_B}{e_A} \tag{2.9}$$

Combining the sensitivity products in equation (2.5), (2.6) and (2.7), the sensitivity of a microphone can be expressed as in equation (2.10), with unit V/Pa.

$$M_A = \sqrt{\frac{V_{a,CA} V_{a,AB}}{V_{a,BC}} \frac{\beta_{CA} \beta_{AB}}{\beta_{BC}} k} \tag{2.10}$$

The sensitivity of a microphone can similarily be described in terms of the acoustic impedance according to equation (2.11). Here $Z_{a,AB}$ is the acoustic transfer impedance between microphone A and microphone B.

$$M_A = \sqrt{\frac{Z_{a,BC}}{Z_{a,CA} Z_{a,AB}} \frac{\beta_{CA} \beta_{AB}}{\beta_{BC}} Z_x} \tag{2.11}$$

Equation (2.10) can also be modified to express the sensitivity in decibels according to equation (2.12)

$$S_A = 10 \cdot \log_{10}(|\frac{V_{a,CA} V_{a,AB}}{V_{a,BC}} \frac{\beta_{CA} \beta_{AB}}{\beta_{BC}} k|) \tag{2.12}$$

While the pressure sensitivity level is expressed in dB re 1 V/Pa the phase associated with the pressure sensitivity is expressed in degrees. The sensitivity phase is converted to approach 180 ° at low frequencies and is 90 ° at the resonance frequency of the microphone.

2.4 Acoustic volume

The acoustic transfer impedance of a plane-wave coupler with microphones A and B is given by equation (2.13), where $Z_{a,A}$ is the acoustic impedance of microphone A, $Z_{a,0}$ is the acoustic impedance of plane waves in the cavity and γ is the complex propogation coefficient. Assuming no losses in the cavity the complex propagation coefficient can be assumed to be purely imaginary and given as $j\omega/c$, with c being the speed of sound in air. Similarily, $Z_{a,0}$ can assuming no losses in the cavity be approximated as $\frac{\rho c}{S_0}$, with ρ being the density of air and S_0 being the cross-section area of the coupler. l_{AB} is here the distance between the membranes of the microphones [2].

$$\frac{1}{Z_{a,AB}} = (\frac{1}{Z_{a,A}} + \frac{1}{Z_{a,B}})\cosh(\gamma l_{AB}) + \frac{1}{Z_{a,0}}(1 + \frac{Z_{a,0}^2}{Z_{a,A}Z_{a,B}})\sinh(\gamma l_{AB}) \tag{2.13}$$

Using equation (2.1), an expression for the acoustic volume can be derived acording to equation (2.14).

$$V_{a,AB} = (V_{a,A} + V_{a,B})\cosh(\gamma l_{AB}) + (\frac{\kappa P_s}{j\omega Z_{a,0}} + V_{a,A}V_{a,B}\frac{j\omega Z_{a,0}}{\kappa P_s})\sinh(\gamma l_{AB}) \tag{2.14}$$

The acoustic volume of the microphone with index A is given by equation (2.15), where κ and and P_s are the measured values of the specific heat ratio and barometric pressure, whereas κ_r and $P_{s,r}$ are the corresponding values at reference conditions. $V_{e,A}$ is the equivalent volume of the microphone and $V_{k,A}$ is the volume of the front cavity of the microphone not included in the geometrical volume of the cavity, measured using data fitting with couplers of different length [6].

$$V_{a,A} = V_{k,A} + \frac{\kappa P_s}{\kappa_r P_{s,r}} V_{e,A} \tag{2.15}$$

The equivalent volume of a condenser microphone is given by equation (2.16), where C_a is the acoustic compliance of the microphone, L_a is the acoustic mass of the microphone and R_a is the acoustic resistance of the microphone. Nominal values for these parameters are given from the manufacturer as in Table 2.1, however these values can be determined more accurately for the individual microphones from measurements.

$$V_e = \kappa P_s C_a \frac{1 - \omega^2 L_a C_a - j\omega R_a C_a}{(1 - \omega^2 L_a C_a)^2 + (\omega R_a C_a)^2} \tag{2.16}$$

The geometrical volume is defined as the cross-section area of the coupler times the the sum of the length of the coupler and the cavity depth of the microphones. The cavity depths of the microphones are measured using a deep focusing microscope [6].

Table 2.1: Nominal microphone data [6].

	B&K 4180	B&K 4134	B&K 4144/60	
C_a	$6.48{\cdot}10^{-14}$	$7.04{\cdot}10^{-14}$	$9.58{\cdot}10^{-13}$	m^5/N
L_a	808	743	393	kg/m^4
R_a	$1.17{\cdot}10^{8}$	$1.17{\cdot}10^{8}$	$2.13{\cdot}10^{7}$	Ns/m^5

2.5 Reference capacitance

The reference impedance, Z_x, determines the ratio between the input current and the corresponding input voltage. By choosing the reference impedance to be purely capacative, the frequency terms in the k-variable are cancelled. The value of the reference impedance should be chosen to make the magnitudes of the input and output voltages as equal as possible in the insert voltage measurement. The calibration of the electrical impedance should include the cable impedance and other load impedances present when measuring the voltage across it [2].

The reference capacitance has been calibrated at a number of frequecies between 31 Hz and 25 kHz, with straight interpolation used to acquire values for the capacitance at frequencies between these [6].

2.6 Electrical transfer impedance

The electrical transfer impedance describes the transfer from the current through the transmitter microphone to the unloaded voltage of the receiver microphone. This transfer function is described in equation (2.17), where U_C is the voltage over the reference capacitance, U_M is the voltage from the receiver microphone, U_A is a calibration signal through the capacitance measurement channel and U_B is a calibration signal through the receiver channel including the microphone [6]. C is the reference capacitance.

$$Z_{e,xy} = \frac{R_{xy}}{C} = \frac{U_M}{U_C}\frac{U_A}{U_B}\frac{1}{C} \tag{2.17}$$

The calibration signals are measured using the insert voltage method. Relays in the calibration apparatus are then set to isolate the driving signal from the transmitter microphone and instead direct it to drive the diaphragm of the receiver microphone. This insert voltage is then identical to the open-circuit voltage of the receiver microphone given no loading of the input impedance of the preamplifier [4]. With this insert voltage applied the voltage on both sides are the calibration signals, and the ratio is divided by the measurement signal ratio.

2.7 Signal analysis

The voltage ratios for the measurement signal and calibration signal are measured for the excitation frequency using the frequency response function. To be able to correctly sample a signal the Nyquist criteria needs to be met. The Nyquist criteria states that the sampling rate needs to be more than twice the highest frequency expected to be encountered. As the frequency range of the B&K 4180 1/2-inch microphones goes up to 20 kHz we need to sample at a rate higher than 40 kHz. Calibration is made for frequencies up to 25 kHz so it is desirable to have an even higher sampling frequency.

Undersampling a signal leads to frequencies above half the sample frequency being interpreted as lower frequencies, thus contributing to bad results even at frequencies below half the sample frequency. This phenomena is known as aliasing.

2.8 Correction factors

2.8.1 Heat conduction

Close to the walls in the cavity the pressure variations are no longer purely adiabatic. This because some of the created temperature variations due to the varying pressure is led to the coupler itself. The correction factor at low frequencies, where the sound pressure can be assumed to be the same at all points in the coupler, for this effect is given by equation (2.18), where E_V is the temperature transfer function [2]. This factor is multiplied to the sinh-term in equation (2.13) as an increased acoustic volume.

$$\Delta_H = \frac{\kappa}{1 + (\kappa - 1)E_V} \tag{2.18}$$

Equation (2.19) is used to calculate the temperature transfer function. The parameters S, D_1 and D_2 are given by equations (2.20)-(2.22). Here $X = fl^2/(\kappa\alpha_t)$, where f is the frequency of the driving signal, l is the volume to surface ratio of the coupler and α_t is the thermal diffusivity of the enclosed gas given in square meters per second. R is the length to diameter ratio of the coupler [2].

$$E_V = 1 - S + D_1 S^2 + \frac{3}{4}\sqrt{\pi} D_2 S^3 \tag{2.19}$$

$$S = \sqrt{-j\frac{1}{2\pi X}} = \frac{1 - j}{2\sqrt{\pi X}} \tag{2.20}$$

$$D_1 = \frac{\pi R^2 + 8R}{\pi(2R + 1)^2} \tag{2.21}$$

$$D_2 = \frac{R^3 - 6R^2}{3\sqrt{\pi}(2R + 1)^3} \tag{2.22}$$

The surface area of the enclosed volume is used in the calculation of the heat correction, and due to the fact that some microphone types have threads and pockets that increase the surface an extra contribution to the cavity depth of the microphones are added according to Table 2.2.

Table 2.2: Extra contributions to the cavity depth due to threads and pockets [6].

Microphone type	B&K 4180	B&K 4134	B&K 4144	B&K 4160
Depth contribution	0 mm	0 mm	1.6 mm	0.5 mm

At high frequencies we will have to consider viscous losses as well as the thermal losses in the coupler. The viscous losses lead to a reduction in the effective cross-section area of the coupler, due to the boundary layer next to the surface, as well as an increase of the effective length of the coupler, due to reduced speed of sound [2]. These effects will cancel out at low frequencies but at high frequencies they will have to be considered.

For the broad-band solution correction for heat conduction is made on the propagation coefficient, the acoustic impedance of the coupler and the acoustic admittance of the microphones. The correction to the propagation coefficient is given by equation (2.23), where a is the radius of the coupler and η is the viscosity of air. The correction to the acoustic impedance of the coupler is given by equation (2.24), while the correction to the microphone impedance is given as an acoustic admittance added to the admittance of the microphones. This extra contribution to the admittance of the microphones is calculated according to equation (2.25).

$$\gamma = j\frac{\omega}{c}(1+\frac{1-j}{\sqrt{2}}\frac{1}{a}(\sqrt{\frac{\eta}{\omega\rho}}+(\kappa-1)\sqrt{\frac{\alpha_t}{\omega}})) \tag{2.23}$$

$$Z_{a,0} = \frac{\rho c}{S_0}(1+\frac{1-j}{\sqrt{2}}\frac{1}{a}(\sqrt{\frac{\eta}{\omega\rho}}-(\kappa-1)\sqrt{\frac{\alpha_t}{\omega}})) \tag{2.24}$$

$$\frac{1}{Z_{a,h}} = \frac{S_0}{\rho c}\frac{1+j}{\sqrt{2}}(\kappa-1)\frac{1}{c}\sqrt{\alpha_t\omega} \tag{2.25}$$

The increased surface due to threads and pockets is here accounted for by an increase of the cross-section area S_0 in equation (2.25). The increase in surface area for the standard laboratory microphones are given in Table 2.3.

Table 2.3: Extra contributions to the surface area due to threads and pockets [5].

Microphone type	B&K 4180	B&K 4134	B&K 4144	B&K 4160
Surface contribution	0 mm^2	0 mm^2	331 mm^2	81 mm^2

This broad-band solution is valid above 3 Hz for calibration with plane-wave coupler and 1-inch microphones and above 12 Hz for calibration with plane-wave coupler and 1/2-inch microphones [2]. When applying the broad-band solution the low-frequency heat correction is set to one.

2.8.2 Capillary tubes

In order to acquire the same pressure inside and outside the cavity capillary tubes can be used, whereby a correction factor is used in the calculations. However since the calibration system used at SP does not include capillary tubes, this report treats the case of blocked capillary tubes.

2.8.3 Barometric pressure

The reference value of the barometric pressure used in calculations is $P_{s,r}$ =101.325 kPa, and the accepted range in which the measurement can be conducted is 98-101.5 kPa [6]. Normalization to reference temperature is acquired from a ninth-order (with respect to the frequency to resonance frequency ratio) polynomial approximation of the results from measurements from 200 Hz to 40 kHz at static pressures between 90 kPa and 110 kPa, with steps of 5 kPa. The measurements led to the approximation that a pressure sensitivity S_p acquired from measurement given a certain atmospheric pressure P_s can be normalized to reference pressure $P_{s,r}$ according to equation (2.26), with δ_p being a complex pressure coefficient dependent on the type of condenser microphone and the ratio between the frequency and the resonance frequency of the microphone, given in B&K Technical Review No.1 2001 [5]. The resonance frequency of the microphone can be calculated either as the frequency where the sensitivity phase is 90 ° or according to equation (2.27), where L_a is the acoustic mass of the diaphragm and C_a is the acoustic compliance of the microphone [2]. Typical values for the resonance frequency are 8.4 kHz for B&K 4160 microphones and 22 kHz for B&K 4160 microphones [5].

$$S_{p,r} = S_p + \delta_p(P_{s,r} - P_s)\, dB\, re\, 1\, V/Pa \tag{2.26}$$

$$f_0 = \frac{1}{2\pi\sqrt{L_a C_a}} \tag{2.27}$$

2.8.4 Temperature

For the temperature the corresponding reference value is t_r =23 °C, with measurements allowed between 20 °C and 25 °C. The temperature dependency is mainly due to expansion of the material in the microphones [6]. Similarily to the pressure normalization, a pressure sensitivity S_p acquired from measurement given a certain temperature t can be normalized to reference pressure t_r according to equation (2.28), with δ_t being a complex temperature coefficient dependent on the type of condenser microphone and the ratio between the frequency and the resonance frequency of the microphone. This coefficient is also given in B&K Technical Review No.1 2001 [5], and is a ninth order approximation acquired from data fitting of measurements between 200 Hz and 40 kHz at four temperatures between 15 °C and 30 °C, in steps of 5 °C.

$$S_{p,r} = S_p + \delta_t(t_r - t)\, dB\, re\, 1\, V/Pa \tag{2.28}$$

2.8.5 Humidity

The relative humidity when conducting measurements has to be in the range between 30-70 %, with the reference value being 50 %. No normalization is made for the humidity, as the effects will be negligble within the allowed range.

2.9 Physical properties of air

The parameters a_i, $i = 0,1,2,...,15$ used throughout this section are given in Report PL-11b [7]. Note that the parameters are individual to the physical property of air being calculated.

2.9.1 Density of humid air

The density of humid air is calculated according to equation (2.29), where Z is the compressibility factor given by equation (2.30) and x_w is the mole fraction of vapor water given by equation (2.31).

$$\rho_0 = [3.483740 + 1.4446(x_c - 0.0004)] \cdot 10^{-3} \frac{P_s}{ZT}(1 - 0.3780x_w) \tag{2.29}$$

$$Z = 1 - \frac{P_s}{T}[a_0 + a_1 t + a_2 t^2 + (a_3 + a_4 t)x_w + (a - 5 + a_6 t)x_w^2] + \frac{P_s^2}{T^2}(a_7 + a_8 x_w^2) \tag{2.30}$$

$$x_w = \frac{H}{100}\frac{P_{sv}(t)}{P_s} f(P_s,t) \tag{2.31}$$

Here P_{sv} is the saturation water vapor pressure given by equation (2.32) and $f(P_s,t)$ is the enhancement factor given by equation (2.33). H is the relative humidity while t and T is the thermodynamic temperature expressed in $^{\circ}C$ and K, respectively.

$$P_{sv}(t) = exp(a_0 T^2 + a_1 T + a_2 + a_3 T^{-1}) \tag{2.32}$$

$$f(P_s,t) = a_0 + a_1 P_s + a_2 t^2 \tag{2.33}$$

2.9.2 Speed of sound in air

Neglecting dispersion, the speed of sound in air is given by equation (2.35), where x_c is the mole fraction of carbon dioxide in air.

$$\begin{aligned} c_0 = a_0 + a_1 t + a_2 t^2 + (a_3 + a_4 t + A - 5t^2)x_w + (a_6 + a_7 t + a_8 t^2)P_s \\ +(a_9 + a_{10} t + a_{11} t^2)x_c + a_{12} x_w^2 + a_{13} P_s^2 + a_{14} x_c^2 + a_{15} x_w P_s x_c \end{aligned} \tag{2.34}$$

2.9.3 Ratio of specific heats

The ratio of specific heats is the ratio between the heat capacity at constant pressure and the heat capacity at constant temperature, and is calculated using equation (2.36). For air at room temperature the ratio of specific heats κ =1.40 [3].

$$\begin{aligned}\kappa = a_0 + a_1 t + a_2 t^2 + (a_3 + a_4 t + a_5 t^2) x_w + (a_6 + a_7 t + a_8 t^2) P_s \\ + (a_9 + a_{10} t + a_{11} t^2) x_c + a_{12} x_w^2 + a_{13} P_s^2 + a_{14} x_c^2 + a_{15} x_w P_s x_c\end{aligned} \tag{2.35}$$

2.9.4 Viscosity of air

The viscosity of air is calculated using equation (2.36).

$$\eta = (a_0 + a_1 T + (a_2 + a_3 T) x_w + a_4 T^2 + a_5 x_w^2) \cdot 10^{-8} \tag{2.36}$$

2.9.5 Thermal diffusivity of air

The thermal diffusivity of air is given by equation (2.37), where k_a is the thermal conductivity given by equation (2.38) and C_p is the specific heat capacity at constant pressure given by equation (2.39).

$$\alpha_t = \frac{k_a}{\rho C_p} \tag{2.37}$$

$$k_a = 4186.8 \cdot [a_0 + a_1 T + a_2 T^2 + (a_3 + a_4 T) x_w] \cdot 10^{-8} \tag{2.38}$$

$$C_p = 4186.8 \cdot [a_0 + a_1 T + a_2 T^2 + a_3 T^3 + (a_4 + a_5 T + a_6 T^2) x_w + (a_7 + a_8 T + a_9 T^2) x_w^2] \tag{2.39}$$

3

Method

3.1 Equipment

Table 3.1: Equipment used in the measurements.

Reciprocity Calibration Apparatus	Bruel & Kjaer 4143, Serial no. 563102
Data acquisition system	National Instruments PXI-1036 DC
Data acquisition module	National Instruments PXI-4462
Multifunction DAQ module	National Instruments PXI-6281
Connector block	National Instruments BNC-2110
Direct laptop control	National Instruments ExpressCard-8360 kit
Polarization voltage source	Newport 2004, Serial no. 3370458
Microphone pre-amplifier	Bruel & Kjaer 2645
Switch/Control Unit	Hewlett-Packard 3488A
USB to GPIB	National Instruments GPIB-USB-HS
Digital pressure indicator	Druck DPI 140
Temperature sensor	Comark C9001
Voltage divider box	

3.2 Equipment settings

Bruel & Kjaer 4143	
Function Selector	Sensitivity Product
Insert Gain	Max
Gain	20 dB
Transmitter/Actuator	Transmitter
Coupler Volume	3 cm^3
Sensitivity Product	0.0 dB
Int/Ext Filter	External
Polarization voltage adjusted to 200.00 V	
Short-circuit in ”Comparator Input A” and ”-B”, respectively	

3.3 Setup

The instruments are connected as shown in Figure 3.1. The oscillator input of the 4143 reciprocity calibration apparatus is connected to the analog output 0 port of the NI BNC-2110 shielded connector block, which in turn is connected to the NI PXI-6281 high accuracy multifunction M series DAQ module installed in the NI PXI-1036 DC DAQ system. Channel A of the reciprocity calibration apparatus is connected to the analog input 0 port of the NI PXI-4462 high-accuracy data acquisition module installed in the DAQ system, while channel B of the reciprocity calibration apparatus is connected to the analog input 1 port of the module. The DAQ system is connected to the computer through a NI ExpressCard-8360.

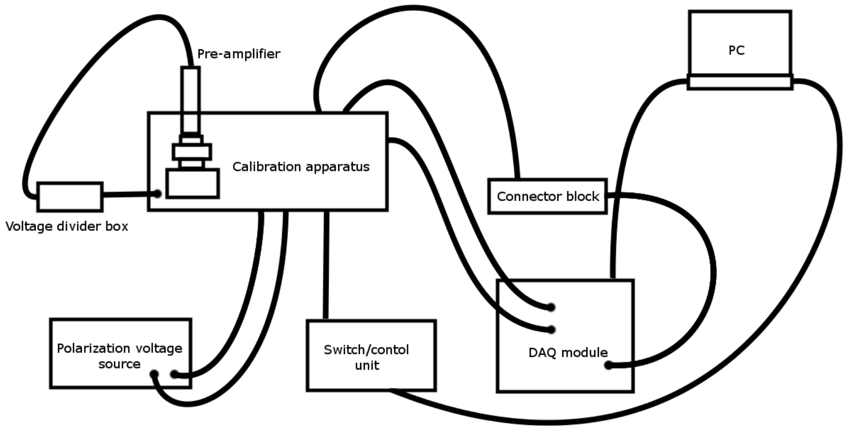

Figure 3.1: Instrument connections for the measurement system.

The transmitter microphone is screwed onto the transmitter microphone socket with standardized ground shield situated in the retractable drawer from the calibration apparatus. The coupler is mounted on top of the transmitter microphone and the receiver microphone is connected to a preamplifier of type 2645 and placed on the coupler, whereby a spring device is set up to keep the microphones tightly against the coupler. The preamplifier is connected through a voltage divider to the preamplifier input of the reciprocity calibration apparatus. The voltage divider adjusts the supply voltage to the preamplifier to 28 V.

To get the instruments to working temperature they are turned on the day before the measurements. Before the first measurement, with the microphones at the measurement positions, the polarization voltage for the microphones is adjusted to 200 V by a screw inside the chassi of the reciprocity calibration apparatus.

To eliminate any vibrational movements from the table on which the calibration apparatus is situated affecting the measurement the apparatus is placed on a plate on top of an isolating layer. A fan is placed some meters from the apparatus and directed towards the setup to even out temperature differences around the setup.

The microphone and the coupler surfaces should be clean and free of dust, which could otherwise cause false air venting in the system. After placing the microphones in the coupler time should be given for pressure stabilisation in the cavity before the start of each measurement, this usually takes 2-5 minutes [6].

In Figure 3.2 the reciprocity calibration apparatus can be seen prepared with a pair of B&K 4180 1-inch laboratory standard microphones connected by a coupler. The figure also shows the polarization voltage source, the temperature sensor and the voltage divider box, from which the preamplifier cable is connected to the preamplifier on the receiver microphone.

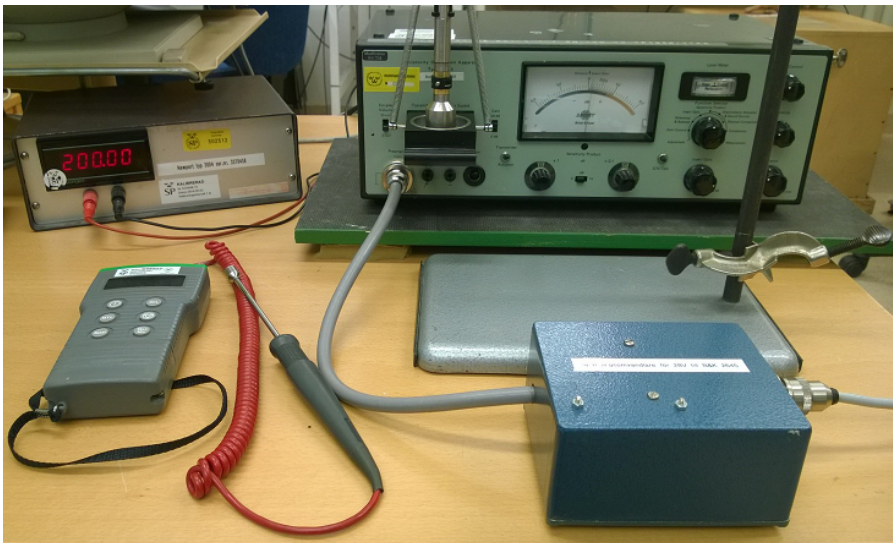

Figure 3.2: The reciprocity calibration apparatus prepared with two 1/2-inch microphones connected by a coupler.

3.4 Measurement

The external signal generator connected to the reciprocity calibration apparatus excites the transmitter microphone. The current through the transmitter microphone is measured over the reference capacitance. Two different control signals are used to set four relays in the reciprocity calibration apparatus to acquire the desired signals in the output channels, done through a switch control unit which in turn is controlled from the laptop through a USB to GPIB cable. These control voltages will enable measurements of the voltage ratios and insert voltages on both transmitter and receiver side in the calibration setup.

After each measurement the microphones are rearranged and another measurement is conducted. Two measurements are made for each pair of microphones, so that each microphone gets to be both transmitter and receiver of sound in each combination. After each microphone combination is measured the temperature is taken at two locations on the measurement setup, near each microphone position. The static air pressure is also noted after each measurement, from a digital pressure indicator.

3.5 Data analysis

The data is acquired using LabVIEW Signal Express, and the data is transferred to LabVIEW where the data analysis is conducted to acquire the sensitivity of the microphones. The frequency response function of the signal is used to enable a good calculation of the voltage ratios in the measurements. The sampling rate is set to 100 kHz with the number of samples read being 100 000 . The data acquired is expressed in terms of magnitude and phase. The sensitivity phase is converted to approach 180 ° at low frequencies and 90 ° at the resonance frequency of the microphone, as prescribed by the key comparison instructions.

Since the transfer impedances are acquired for the microphone combinations in both directions two microphone sensitivities are measured for each microphone, whereby the mean value of these are taken as the sensitivity of the microphone. Measuring the transfer impedance in both directions gives some verification that no measurement has gone bad as well as a check of the reciprocity of the microphones.

Since the temperature and static pressure is noted after each measurement the acoustic volume is calculated for each pair of microphones using the corresponding temperature and static pressure.

The broad-band solution for the heat conduction correction is used in the calculation of the pressure sensitivity. This enhances the accuracy of the calibration at high frequencies.

The program saves the data to a spreadsheet file. This file contains the microphone parameters, the senitivities at measurement climate as well as at reference climate, the raw data in form of the transfer impedances from the measurements and the values of the climate parameters at which the calibration was conducted.

4

Results

4.1 Reference calibrations

In 1998 the B&K 4160 1-inch laboratory standard microphone with serial number 1144809 and the B&K 4180 1/2-inch laboratory standard microphone with serial number 1395447 were sent to Technical University of Denmark for reference calibration.

4.1.1 1-inch microphones

The sensitivities acquired from the calibration of 1-inch microphone 1144809 are presented in Table 4.1. This calibration was conducted at temperature 23 °C, static air pressure 995 mBar and relative humidity 46 %.

Table 4.1: Calibrated pressure sensitivities for microphone 1144809 at Technical University of Denmark.

	Microphone 1144809
Frequency [Hz]	Sensitivity level [dB]
31.5	-26.78
63	-26.82
125	-26.85
245	-26.87
500	-26.87
1000	-26.85
1250	-26.83
1600	-26.79
2000	-26.73
2500	-26.65
3150	-26.53
4000	-26.38
5000	-26.27
6300	-26.43
8000	-27.55
10000	-30.48

4.1.2 1/2-inch microphones

The sensitivities acquired from the calibration of 1/2-inch microphone 1395447 are presented in Table 4.2. This calibration was conducted at temperature 23 °C, static air pressure 993 mBar and relative humidity 43 %.

Table 4.2: Calibrated pressure sensitivities for microphone 1395447 at Technical University of Denmark.

	Microphone 1395447
Frequency [Hz]	Sensitivity level [dB]
31.5	-38.78
63	-38.79
125	-38.80
245	-38.81
500	-38.82
1000	-38.82
1250	-38.81
1600	-38.81
2000	-38.79
2500	-38.77
3150	-38.74
4000	-38.69
5000	-38.60
6300	-38.48
8000	-38.30
10000	-38.09
12500	-37.93
16000	-38.18
20000	-39.43
25000	-41.75

4.2 Previous calibration system

4.2.1 1-inch microphones

A calibration of three at SP currently used B&K 4160 1-inch laboratory standard microphones using the previously used calibration system gives results according to Table 4.3. The calibration was conducted at a temperature around 23.6 °C, a static air pressure around 983 mBar and a relative humidity of 48 %.

Table 4.3: Calibrated pressure sensitivities for microphones for 1-inch microphones, using old system.

	Microphone 1144809	Microphone 1503404	Microphone 1886239
Frequency [Hz]	Sensitivity level [dB]	Sensitivity level [dB]	Sensitivity level [dB]
31.5	-26.748	-27.231	-27.225
63	-26.795	-27.284	-27.277
125	-26.831	-27.325	-27.311
245	-26.855	-27.355	-27.335
500	-26.866	-27.368	-27.346
1000	-26.845	-27.341	-27.324
1250	-26.827	-27.316	-27.304
1600	-26.789	-27.264	-27.264
2000	-26.736	-27.189	-27.205
2500	-26.658	-27.076	-27.118
3150	-26.540	-26.896	-26.982
4000	-26.396	-26.644	-26.801
5000	-26.295	-26.382	-26.644
6300	-26.464	-26.314	-26.693
8000	-27.593	-27.297	-27.633
10000	-30.440	-30.307	-30.148

The results from the last international key comparison of B&K 4160 1-inch laboratory standard microphones show that the sensitivities calibrated at SP deviated from the mean values from all calibrations according to table 4.4.

Table 4.4: Deviation of results calibrated at SP, 1-inch microphones [8].

Frequency [Hz]	Deviation [dB]	Uncertainty [dB]
63	0.00	0.05
125	0.01	0.04
250	0.01	0.04
500	0.00	0.04
1000	0.01	0.04
1250	0.01	0.04
1600	0.00	0.04
2000	0.00	0.04
2500	-0.01	0.04
3150	0.00	0.05
4000	0.00	0.05
5000	0.00	0.06
6300	0.01	0.07
8000	0.03	0.10
10000	0.12	0.20

4.2.2 1/2-inch microphones

A calibration of three at SP currently used B&K 4180 1/2-inch laboratory standard microphones using the previously used calibration system gives results according to Table 4.5. The calibration was conducted at a temperature around 23.4 °C, a static air pressure around 984 mBar and a relative humidity of 46 %.

Table 4.5: Calibrated pressure sensitivities for 1/2-inch microphones, using old system.

	Microphone 1395447	Microphone 1395449	Microphone 1893454
Frequency [Hz]	Sensitivity level [dB]	Sensitivity level [dB]	Sensitivity level [dB]
31.5	-38.783	-37.734	-38.194
63	-38.783	-37.738	-38.201
125	-38.794	-37.756	-38.214
245	-38.808	-37.769	-38.228
500	-38.817	-37.779	-38.237
1000	-38.815	-37.777	-38.236
1250	-38.813	-37.774	-38.234
1600	-38.806	-37.767	-38.228
2000	-38.794	-37.755	-38.217
2500	-38.775	-37.736	-38.198
3150	-38.741	-37.702	-38.166
4000	-38.687	-37.647	-38.114
5000	-38.607	-37.568	-38.039
6300	-38.488	-37.448	-37.924
8000	-38.313	-37.279	-37.757
10000	-38.107	-37.090	-37.565
12500	-37.968	-36.002	-37.443
16000	-38.286	-37.456	-37.817
20000	-39.505	-38.841	-39.208
25000	-41.918	-41.385	-42.052

The results from the last international key comparison of B&K 4180 1/2-inch laboratory standard microphones show that the sensitivities calibrated at SP deviated from the mean values from all calibrations according to table 4.6.

Table 4.6: Deviation of results calibrated at SP, 1/2-inch microphones [9].

Frequency [Hz]	Deviation [dB]	Uncertainty [dB]
31.5	0.003	0.108
63	0.015	0.080
125	0.019	0.052
245	0.018	0.052
500	0.018	0.052
1000	0.020	0.052
2000	0.018	0.052
4000	0.018	0.052
6300	0.021	0.060
8000	0.016	0.060
10000	0.018	0.078
12500	0.012	0.098
16000	-0.007	0.118
20000	-0.017	0.195
25000	-0.093	0.298

4.3 New calibration system

4.3.1 1-inch microphones

The sensitivities acquired from calibration of three B&K 4160 laboratory standard microphones, conducted using the new calibration system, are presented in Table 4.7. The temperature during the measurements was around 23.3 °C, the static air pressure was around 992.9 mBar and the relative humidity was 47 %. In table 4.8 the corresponding phase is presented.

Table 4.7: Calibrated pressure sensitivities for 1-inch microphones.

	Microphone 1144809	Microphone 1503404	Microphone 1886239
Frequency [Hz]	Sensitivity level [dB]	Sensitivity level [dB]	Sensitivity level [dB]
31.5	-26.740	-27.219	-27.207
63	-26.793	-27.283	-27.266
125	-26.831	-27.328	-27.304
245	-26.858	-27.360	-27.331
500	-26.870	-27.374	-27.343
1000	-26.848	-27.346	-27.321
1250	-26.829	-27.319	-27.300
1600	-26.792	-27.268	-27.261
2000	-26.738	-27.192	-27.203
2500	-26.658	-27.075	-27.114
3150	-26.540	-26.894	-26.978
4000	-26.388	-26.632	-26.792
5000	-26.283	-26.359	-26.627
6300	-26.448	-26.280	-26.679
8000	-27.582	-27.255	-27.614
10000	-30.484	-30.336	-30.212

Table 4.8: Acquired phase from calibration of pressure sensitivities for 1-inch microphones.

	Microphone 1144809	Microphone 1503404	Microphone 1886239
Frequency [Hz]	Phase [°]	Phase [°]	Phase [°]
31.5	178.4	178.3	178.3
63	178.6	178.5	178.6
125	178.4	178.4	178.4
245	177.7	177.8	177.8
500	175.9	176.3	176.2
1000	172.3	173.0	172.7
1250	170.4	171.3	171.0
1600	167.7	168.9	168.5
2000	164.5	166.0	165.5
2500	160.3	162.3	161.6
3150	154.5	157.0	156.2
4000	146.2	149.2	148.4
5000	135.1	138.4	137.9
6300	118.7	121.5	122.0
8000	95.1	96.2	99.1
10000	72.9	71.6	75.7

In Figure 4.1 the sensitivities of microphone 1144809 acquired from reference calibration at Technical University of Denmark and from calibration using the old and new system are compared.

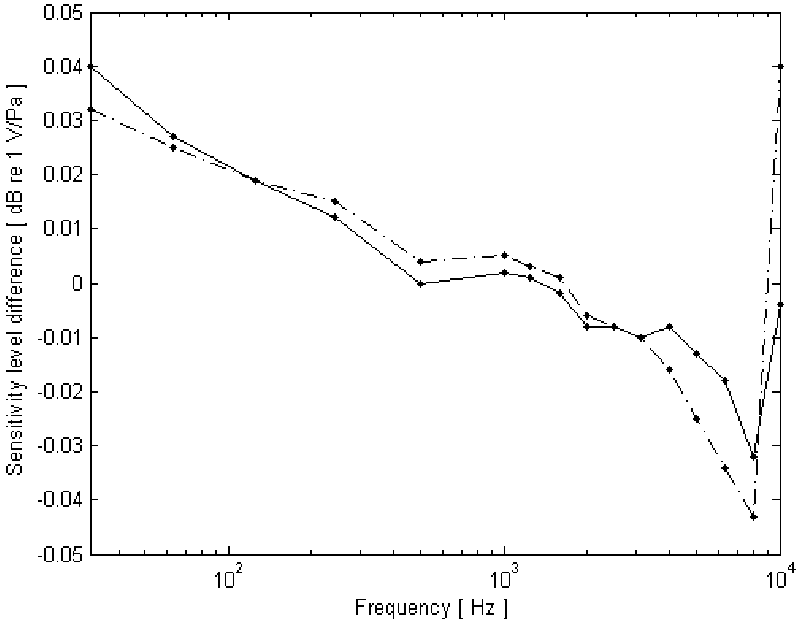

Figure 4.1: Difference in calibrated sensitivity between reference calibration and calibration using old system (dashed line) and difference in calibrated sensitivity between reference calibration and calibration using new system (solid line), 1-inch microphone 1144809.

In Figure 4.2 the sensitivities of microphone 1144809 acquired from from calibration using the old and new system are compared along with the difference in calibrated sensitivities acquired from the old system and the mean results from the last international key comparison.

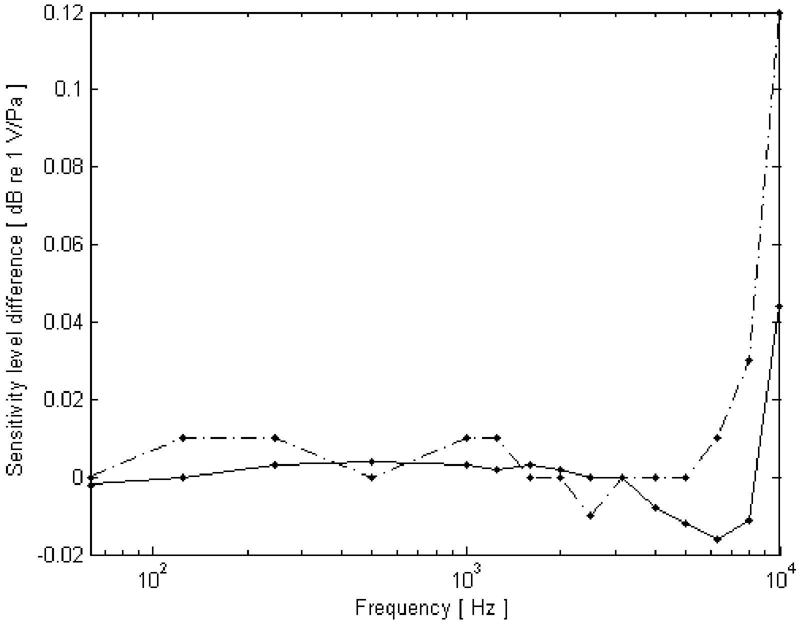

Figure 4.2: Difference between mean result from last key comparison and calibration using old system (dashed line) as well as difference in calibrated sensitivity between calibration using new system and old system (solid line), 1-inch microphone 1144809.

4.3.2 1/2-inch microphones

The sensitivities acquired from calibration of three B&K 4180 laboratory standard microphones, conducted using the new calibration system, are presented in Table 4.7. The temperature during the measurements was around 22.9 °C, the static air pressure was around 995.9 mBar and the relative humidity was 48 %. In table 4.10 the corresponding phase is presented.

Table 4.9: Calibrated pressure sensitivities for 1/2-inch microphones.

	Microphone 1395447	Microphone 1395449	Microphone 1893454
Frequency [Hz]	Sensitivity level [dB]	Sensitivity level [dB]	Sensitivity level [dB]
31.5	-38.758	-37.709	-38.165
63	-38.774	-37.732	-38.186
125	-38.795	-37.754	-38.209
245	-38.814	-37.773	-38.228
500	-38.826	-37.786	-38.242
1000	-38.829	-37.788	-38.244
1250	-38.827	-37.786	-38.242
1600	-38.820	-37.779	-38.236
2000	-38.809	-37.767	-38.225
2500	-38.790	-37.747	-38.207
3150	-38.756	-37.714	-38.175
4000	-38.701	-37.658	-38.123
5000	-38.621	-37.576	-38.045
6300	-38.497	-37.452	-37.927
8000	-38.321	-37.281	-37.759
10000	-38.121	-37.098	-37.571
12500	-37.962	-36.996	-37.425
16000	-38.214	-37.384	-37.738
20000	-39.446	-38.789	-39.161
25000	-41.794	-41.239	-41.957

Table 4.10: Acquired phase from calibration of pressure sensitivities for 1/2-inch microphones.

	Microphone 1395447	Microphone 1395449	Microphone 1893454
Frequency [Hz]	Phase [°]	Phase [°]	Phase [°]
31.5	179.8	179.1	179.1
63	179.6	179.2	179.2
125	179.4	179.2	179.2
245	179.1	179.0	179.0
500	178.5	178.4	178.4
1000	177.2	177.1	177.1
1250	176.6	176.4	176.4
1600	175.7	175.4	175.5
2000	174.6	174.3	174.4
2500	173.3	172.9	173.0
3150	171.5	171.1	171.2
4000	169.2	168.6	168.8
5000	166.3	165.6	165.8
6300	162.3	161.3	161.6
8000	156.6	155.3	155.7
10000	149.0	147.3	147.9
12500	138.0	135.6	136.5
16000	120.5	117.4	118.2
20000	100.7	97.7	97.2
25000	81.9	79.7	77.9

In Figure 4.3 the sensitivities of microphone 1395447 from reference calibration at Technical University of Denmark and from calibration using the old and new system are compared.

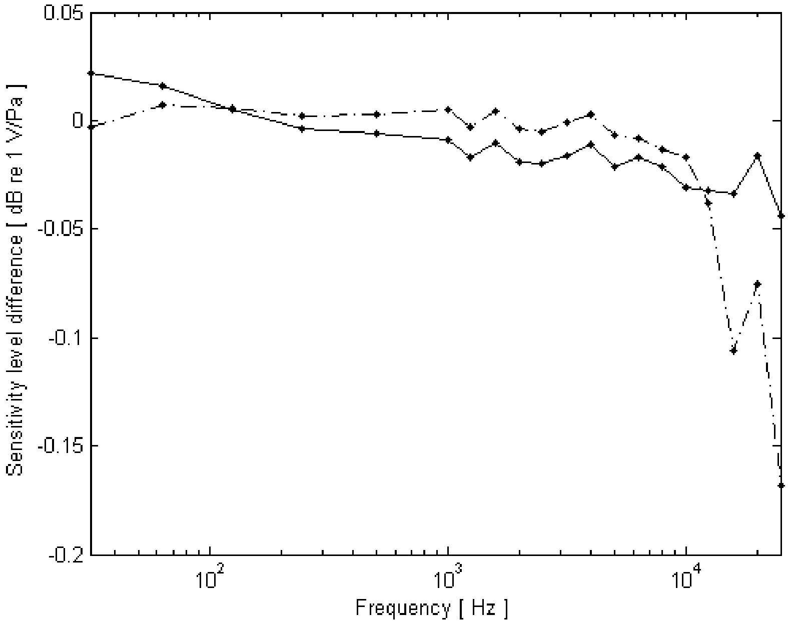

Figure 4.3: Difference in calibrated sensitivity between reference calibration and calibration using old system (dashed line) and difference in calibrated sensitivity between reference calibration and calibration using new system (solid line), 1/2-inch microphone 1395447.

In Figure 4.4 the sensitivities of microphone 1395447 acquired from from calibration using the old and new system are compared along with the difference in calibrated sensitivities acquired from the old system and the mean results from the last international key comparison.

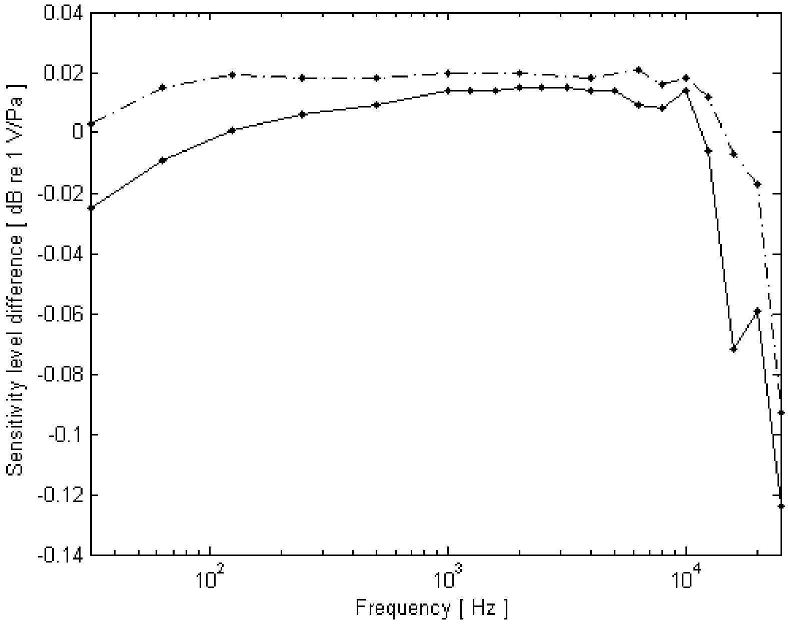

Figure 4.4: Difference between mean result from last key comparison and calibration using old system (dashed line) as well as difference in calibrated sensitivity between calibration using new system and old system (solid line), 1/2-inch microphone 1395447.

4.4 Key comparison

The key comparison of pressure calibration of LS1P microphones is an international intercomparison between national metrology institutes. The measurement phase of the project is being conducted between September 2013 and March 2015, with a draft of the results expected in the summer of 2015. The project consists of the calibration of two B&K 4160 1-inch laboratory standard microphones, with serial numbers 811014 and 2036126, respectively. The calibration is done for the center frequencies of the 1/3-octave bands between 20 Hz and 10 kHz. The center frequencies shall be caculated using equation (4.1), where f_r is 1 kHz and n is an integer between -27 and 17.

$$f_n = f_r \cdot 10^{n/10} \tag{4.1}$$

The acquired sensitivities from calibration of the microphones in the key comparison are presented in Table 4.11. These sensitivities were calibrated at temperature around 23.1 °C, barometric pressure 994 mBar and relative humidity 46 %.

Table 4.11: Calibrated pressure sensitivities for microphones in key comparison.

	Microphone 811014	Microphone 2036126
Frequency [Hz]	Sensitivity level [dB]	Sensitivity level [dB]
19.95	-26.146	-27.320
25.12	-26.177	-27.345
31.62	-26.203	-27.365
39.81	-26.230	-27.385
50.12	-26.249	-27.400
63.1	-26.268	-27.417
79.43	-26.284	-27.429
100	-26.308	-27.453
125.89	-26.312	-27.450
158.49	-26.322	-27.462
199.53	-26.337	-27.475
251.19	-26.341	-27.478
316.23	-26.348	-27.481
398.11	-26.352	-27.485
501.19	-26.352	-27.486
630.96	-26.345	-27.482
794.33	-26.336	-27.474
1000	-26.314	-27.459
1258.93	-26.280	-27.432
1584.89	-26.225	-27.391
1995.26	-26.137	-27.325
2511.89	-26.000	-27.221
3162.28	-25.797	-27.069
3981.07	-25.529	-26.861
5011.87	-25.280	-26.641
6309.57	-25.427	-26.623
7943.28	-26.892	-27.422
10000	-30.477	-30.055

5

Discussion

There are some difficulties when it comes to drawing conclusions from the results. The sensitivities acquired from calibration using the new calibration system can obviously be compared to the sensitivities acquired from the previously used calibration system, however the analysis of the deviations is somewhat more difficult as the new system is desired to exhibit more accurate results than the previous system. There are results from the earlier key calibrations which can be used for comparison, but a straight comparison of the deviations does hold some uncertainty as the changes in the code between the system used in the earlier key comparisons and the replaced system currently available are not properly documented. Therefore caution must be taken when drawing conclusions from these comparisons.

As for the comparisons to sensitivities acquired from calibration using precise measurements at Technical University of Denmark there is some uncertainty due to the fact that these reference calibrations took place in 1998, and there is always a risk that the sensitivity of the microphones could have been altered due to for instance dust and particles acquired on the diaphragm. This is also something we need to keep in mind when drawing conclusions from the results.

Comparing the sensitivities acquired from calibration of B&K 4160 1-inch laboratory standard microphones using the new and old system (see Figure 4.2), the deviations are quite small below 4 kHz. However at frequencies above 4 kHz the new system gives lower sensitivities, except at 10 kHz where the new system gives significantly higher sensitivity. The results from the last key comparison of 1-inch microphones show a somewhat similar pattern at high frequencies, with the old system giving significantly lower sensitivity than the mean value acquired from the key comparison at 10 kHz.

Comparing the sensitivities acquired from calibration of B&K 4180 1/2-inch laboratory standard microphones using the new and old system (see Figure 4.4), the new system seems to give sensitivities that are about 0.01 dB higher than the sensitivities acquired using the old system. However at frequencies below 100 Hz and above 10 kHz the deviation is reversed. At high frequencies the new system gives sensitivities that are well below those acquired from the old system. Looking at the results from the last key comparison of 1/2-inch microphones this behaviour can also be seen in the deviations between the mean values acquired from the key comparison and the sensitivities acquired from the old system, however the deviations are here not quite as large.

The significantly improved results at high frequencies can to a great extent be explained by the application of a broad-band solution of the heat conduction correction, replacing the low-frequency solution used in the previously used calibration system. But also the parameterized temperature normalization applied, as opposed to the earlier lack of temperature normalization, will contribute to improved results mainly at high frequencies.

From the acquired phases it can be seen that the resonance frequency, which is where the phase is 90 °, is between 8 kHz and 10 kHz for the B&K 4160 microphones (see Table 4.8) and between 20 kHz and 25 kHz for the B&K 4180 microphones (see Table 4.10), as is expected [5].

At frequencies close to the resonance frequencies of the microphones the microphone parameters become of great importance with regards to measurement uncertainty. For both the B&K 4180 1/2-inch microphones and the B&K 4160 1-inch microphones the upper frequency limit of the microphones is below the resonance frequency, however calibrations are still being conducted up to 25 kHz for 1/2-inch microphones and to 10 kHz for 1-inch microphones. At these frequencies the results will thus be highly sensitive to any inaccuracies in the microphone parameters.

One of the main sources of measurement uncertainty can be assumed to be the physical placement of the setup of coupler and microphones. As there is some room for variations in the attachment of the microphones to the coupler this will cause deviations to the measured transfer impedances. If there are particles in between the attached surfaces of cavity and microphone ring the cavity will not be sealed, thus causing a significant source of error. The standard uncertainty due to leakage is assumed to be 0.005 dB at 31.5 Hz and decreasing by 0.001 dB per octave up to 500 Hz.

The temperature is another parameter that gives a high uncertainty contribution at high frequencies. As the temperature is taken from two positions on the utside of the setup the deviation can be assumed to be rather big. There is also a question of which temperature is desired to be measured, as the temperature is included in the calculations both with regards to the microphones and the physical properties of the air that fills the cavity. As the temperature sensor indicates the temperature with an uncertainty of 0.1 °C and the temperature is taken on the outside of the setup it is assumed that the maximum deviation from the mean value is 1 °C [6]. This gives a standard uncertainty of 0.6 °C, which corresponds to an uncertainty contribution of 0.01 dB at the upper frequency limit for both the 1-inch and 1/2-inch microphones.

The static pressure will give rise to an uncertainty that is quite uniformly distributed over the frequency range of the microphones. As the static pressure is observed after each microphone pair is measured and the corresponding value is used for each microphone pair in the new calibration system this uncertainty will be considerably smaller than in the previous calibration system, where the mean value of the static pressure was used in the calculations. For this system the uncertainty was estimated to around 0.006 dB [6].

6

Conclusions

As discussed, caution needs to be taken when drawing conclusions from comparison of the results and a definitive answer on the accuracy of the new calibration system will not be available until the results from the international key comparison are published. However comparison with the results from reference calibrations at Technical University of Denmark and earlier international key comparisons indicate that the results acquired from the newly developed calibration system are more accurate than the results acquired from the previously used system. At high frequencies this can be determined to be true, as a clear improvement in the results can be seen. These improvements can to some extent be explained by the updated theory when it comes to corrections and normalizations.

Apart from improved results the system also has advantages in reduced calibration time due to two-channel measurements and frequency response function being used for the measurement of the voltage ratios. Furthermore, the new system also simplifies the calibration procedure due to the new, more user friendly, interface programmed in LabVIEW.

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