CHALMERS
UNIVERSITY OF TECHNOLOGY

# Determination of laboratory standard microphone parameters in reciprocity calibration

Master's thesis in sound and vibration

XUANZHU CHEN

Department of Architecture and civil engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

Master's thesis 2020:ACEX30

# Determination of laboratory standard microphone parameters in reciprocity calibration

XUANZHU CHEN

Department of Architecture and civil engineering
*Division of Sound and Vibration*
Chalmers University of Technology
Gothenburg, Sweden 2020

Determination of laboratory standard microphone parameters in reciprocity calibration
XUANZHU CHEN



Supervisor: Håkan Andersson, Research Institutes of Sweden
Examiner: Jens Ahrens, Department of Architecture and civil engineering

Master's Thesis 2020:ACEX30
Department of Architecture and civil engineering
Division of Sound and Vibration
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover:B&K TYPE 9699 MICROPHONE PRIMARY CALIBRATION SYSTEM.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

Determination of laboratory standard microphone parameters in reciprocity calibration
XUANZHU CHEN
Department of Architecture and civil engineering
Chalmers University of Technology

# Abstract

Reciprocity calibration is one of the most accurate technique to calibrate a primary standard condenser microphone. The calibration procedure is conducted according to IEC 61094-2:2009, including the calculation of acoustical transfer impedance, electrical impedance as well as correction of thermal conduction, radial wave-motion, and ambient pressure temperature. This paper investigates four characteristics of laboratory standard microphone in reciprocity calibration, front cavity depth, equivalent volume, resonance frequency, loss factor, and their influence on the pressure sensitivity level. In order to obtain more accurate calibration results, microphone parameters should be determined for every single laboratory standard microphone, instead of using nominal values provided by the manufacturer in the reciprocity calibration system. Several laboratory methods for every single microphone characteristic are analyzed and the optimal solution is decided based on applicability, time cost, and accuracy evaluation.

Keywords: Microphone characteristics, Front cavity depth, Equivalent volume, Resonance frequency, Loss factor, Uncertainty.

# Acknowledgements

This thesis is conducted at the Research Institutes of Sweden and the department of Sound and Vibration at the Chalmers University of Technology. I am very thankful to my supervisor Håkan Andersson, who brings me to the world of calibration and answers my questions patiently and comprehensively. I would like to express my gratitude to my examiner Jens Ahrens, who taught me in the past two years and gives me an insight into the acoustic field as well as for all the close guidance and support along the way.

Xuanzhu Chen, Gothenburg, August 2020

# Contents

# 1

# Introduction

## 1.1 Background

Microphone calibration is the technique used to determine the transfer coefficient between the output voltage and the sound pressure. Even though some calibration principles have been applied over the century, the methods and facilities are still being refined to minimize the uncertainty, extend the frequency range, and include extra parameters as well as speed up[14]. Because there are more and more requirements for sound measurements in modern society, acoustic metrology has become a very important activity. Reciprocity calibration is one of the most accurate technique to calibrate a primary standard condenser microphone with an uncertainty less than 0.01 dB at 250 Hz under reference environment. A condenser microphone is selected as the measurement and reference standard microphone due to the high mechanical stability and flat frequency response. The calibration procedure is conducted according to IEC 61094-2:2009, including the calculation of acoustical transfer impedance, electrical impedance as well as correction of thermal conduction, radial wave-motion, and ambient pressure temperature. The primary pressure reciprocity calibration is conducted in a pressure field, where the cavity dimensions are smaller than one-quarter of the wavelength. The results can also be transformed into other sound fields by using the correction data supplied by manufacturers.

## 1.2 Goal

The goal of this thesis work is to research different methods to determine the laboratory standard microphone parameters. Simulations of microphone calibration result sensitivity to errors in the microphone parameter determination, as well as some refinement based on the original reciprocity calibration system.

## 1.3 Outline

Chapter 2.9.2 introduces the basic theory related to the thesis work. Chapter 3 lists the experimental methods used to determine the value of the four microphone characteristics, then the method for weighing the relative significance is introduced. Chapter 4 gives all the results plots for pressure sensitivity level, uncertainty, main effect as well as ANOVA tables. In chapter 5 the numerical value of a single characteristic is changed to see the impact on the final pressure sensitivity level and phase results on the whole calibration system. In chapter 6, the treatment of uncertainty is later done for both a single characteristic and the whole system. In Chapter 7, a refinement work is done based on the previous calibration system. By splitting the calculation of acoustic transfer impedance into high and low-frequency ranges and add the correction factors respectively according to IEC 61094-2 Annex A The conclusion is finally drawn in Chapter 8.

# 2

# Theory

## 2.1 Condenser microphone

### 2.1.1 Definition

A condenser microphone is a kind of capacitive sensing transducer. By changing the distance between the two statically charged electrodes, one of which is fixed. the pressure and voltage can be converted. The moving parts of the capsule can be represented as a mass-compliance-resistance system. The first resonance of the the diaphragm is usually high tuned to keep the microphone working in the compliance-controlled range.

### 2.1.2 Characteristics

Compared with electrodynamics microphones, condenser microphones respond faster, have a better high-frequency response, and extended lower and higher frequencies. The condenser microphone will be affected by humidity and temperature. Internal or external is required to charge the electrodes.

### 2.1.3 Laboratory standard microphone

A laboratory standard microphone is a condenser microphone capable of being calibrated to very high accuracy by a primary a method such as the closed coupler reciprocity method, and meeting certain severe requirements on mechanical dimensions and electroacoustical characteristics, especially with respect to stability in time and dependence on environmental conditions.[16] It belongs to a small diaphragm condenser microphone, which only has a single pick up pattern and slightly lower frequency response.

## 2.2 Microphone parameters

### 2.2.1 Front cavity depth

The front cavity depth is defined by the vertical distance between the annulus and the center of the diagram. Which consists of an essential part in calculating the front cavity volume accurately in acoustic transfer impedance Formula 2.5 and 2.6

### 2.2.2 Equivalent diaphragm volume

Equivalent diaphragm volume is the volume of air that has the same compliance as the diaphragm at a static pressure of 101.3 kPa, which is caused by the non-rigidity of the microphone diaphragm. It is used in connection with coupler calibration of microphones and for evaluating the loading which the microphone presents to small couplers. The equivalent volume $V_e$ of a microphone is related to the acoustic impedance by the following equation:

$$V_e = \frac{\kappa_r p_{s,r}}{j\omega Z_a} \tag{2.1}$$

### 2.2.3 Total front volume

Total front volume is the sum of front cavity volume and equivalent diaphragm volume.

### 2.2.4 Resonance frequency

The resonance frequency is the frequency at which the imaginary part of the acoustic impedance $Z_a$ is zero.

### 2.2.5 Loss factor

loss factor is the ratio of the energy dissipated per cycle to maximum strain energy stored.

## 2.3 The equivalent lumped parameters of he acoustic impedance

The acoustic impedance of the microphone can be equally expressed by acoustic mass $m_a$, acoustic compliance $c_a$, acoustic resistance $r_a$, or the resonance frequency $f_0$, equivalent volume at low frequency $V_{eq}$, loss factor d. The relations between them are showing below, where $\gamma_r$ is the reference ratio of specific temperature of gas.

$$(2\pi f_0)^2 = (m_a c_a)^{-1} \tag{2.2}$$

$$V_{eq} = c_a \gamma_r p_{s,r} \tag{2.3}$$

$$d = \frac{r_a}{2\pi f_0 m_a} = r_a 2\pi f_0 c_a \tag{2.4}$$

## 2.4 Acoustic impedance

The acoustic impedance of the microphone is a function of frequency and is determined mainly by the properties of the stretched diaphragm and the air enclosed in the cavity behind the diaphragm, and by the geometry of the backplate.[2]

## 2.5 Acoustic transfer impedance

For a system of two acoustically coupled microphones the quotient of the sound pressure acting on the diaphragm of the microphone used as a receiver by the short-circuit volume velocity produced by the microphone used as a transmitter.[2]

At low frequencies, the gas in the coupler can be assumed as pure compliance in the equivalent circuit in Figure 2.1, the acoustic transfer impedance is calculated according to Equation 2.5. Where $V_{e,1}$ and $V_{e,2}$ are the equivalent volume for transmitter and receiver microphones respectively in cubic meters, $Z_{a,V}$ is the acoustic impedance of the gas enclosed in the coupler in pascal-seconds per cubic meter, $p_s$ is the static pressure in pascals, $p_{s,r}$ is the static pressure at reference conditions in pascals,$\kappa$ is the ratio of the specific heat capacities at measurement conditions and $\kappa_r$ is at reference conditions.

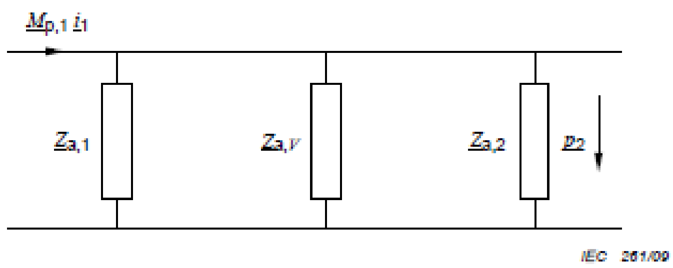



**Figure 2.1:** Equivalent circuit for evaluating $Z_{a,12}$ when coupler dimensions are small compared with wavelength

$$\frac{1}{Z_{a,12}} = \frac{1}{Z_{a,V}} + \frac{1}{Z_{a,1}} + \frac{1}{Z_{a,1}} = j\omega\left(\frac{V}{\kappa p_s} + \frac{V_{e,1}}{\kappa p_s} + \frac{V_{e,2}}{\kappa p_s}\right) \tag{2.5}$$

At high frequencies, plane wave transmission in the coupler can be assumed as shown in Figure . The acoustic transfer impedance is expressed in a more complicated Equation .Where $Z_{a,0}$ is the acoustic impedance of plane waves in the coupler, $l_0$ is the length of the coupler and $\gamma$ is the complex propagation coefficient in metres to power minus one.

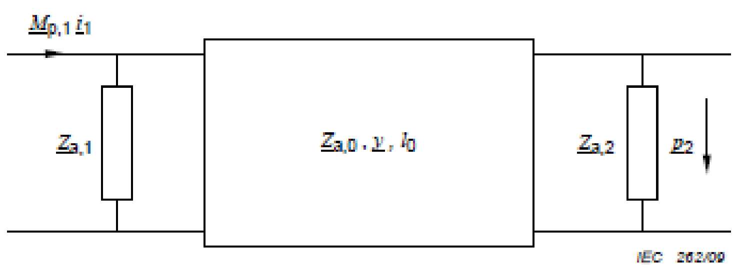



**Figure 2.2:** Equivalent circuit for evaluating $Z_{a,12}$ when plane wave transmission in the coupler can be assumed

$$\frac{1}{Z_{a,12}} = \frac{1}{Z_{a,0}} \left[ \left( \frac{Z_{a,0}}{Z_{a,1}} + \frac{Z_{a,0}}{Z_{a,2}} \right) cosh\gamma l_0 + \left( 1 + \frac{Z_{a,0}}{Z_{a,1}} \frac{Z_{a,0}}{Z_{a,2}} \right) sinh\gamma l_0 \right] \tag{2.6}$$

## 2.6 Electrical transfer impedance

For a system of two acoustically coupled microphones the quotient of the open-circuit voltage of the microphone used as a receiver by the input current through the electrical terminals of the microphone is used as a transmitter.

## 2.7 Reciprocity calibration

There are two methods to carry out the reciprocity calibration, one is using three reciprocal microphones and anther is using an auxiliary sound source combined with two microphones, one of which shall be reciprocal. In this thesis work, only the first one is used. Firstly, two of the three microphones are connected acoustically by a coupler. If the electrical and acoustic transfer impedance is known, the product of the pressure sensitivities of the two coupled microphones can be determined. Using pair-wise combinations of three microphones, three such mutually independent products are available, from which expression for the pressure sensitivity of each of the three microphones can be derived.[2]

The two-ports equation of the microphones can be written as 2.7. Where p is the sound pressure at the diaphragm of the microphone. U is the signal voltage at the electrical terminal of the microphone. q is the volume velocity, i is the current through the electrical terminal. $Z_e$ is the electrical impedance of the microphone when the diaphragm is blocked. $Z_a$ is the acoustic impedance when the electrical terminal is unloaded and $M_p$ is the pressure sensitivity.

$$\begin{aligned} Z_e i + M_p Z_a q &= U \\ M_p Z_a i + Z_a q &= p \end{aligned} \tag{2.7}$$

Define $M_{p,1}$ and $M_{p,2}$ as the sensitivities as two microphones. A current $i_1$ through the electrical terminal will produce a short-circuit volume velocity of $M_{p,1}i_1$, the sound pressure at the acoustical terminal of microphone 2 can be expressed as in equation 2.8. The open circuit voltage of microphone 2 can be written as in equation 2.9. Finally, the product of the pressure sensitivity is given by equation 2.8

$$p_2 = Z_{a,12} M_{p,1} i_1 \tag{2.8}$$

$$U_2 = M_{p,2} p_2 = M_{p,1} M_{p,2} Z_{a,12} i_1 \tag{2.9}$$

$$M_{p,1} M_{p,2} = \frac{1}{Z_{a,12}} \frac{U_2}{i_1} \tag{2.10}$$

## 2.8 Taguchi Method

The Taguchi method developed by Genuchi Taguchi is a statistical method used to improve the product quality, which utilizes the standard orthogonal array and analysis of variance to investigate and determine the optimal level of control factors. [8]

## 2.9 Heat conduction and viscous losses in a closed cavity

The transition from adiabatic to isothermal conditions caused by heat conduction between air and the wall of the coupler depends on the calibration frequency and coupler dimension. Besides, the sound particle velocity along the coupler surfaces results in viscous losses. There are two approaches to determine the sound pressure results.

### 2.9.1 Low frequency solution

At low frequencies, the sound pressure can be assumed to be the same at all points in the coupler, the effect of heat conduction can be considered as an apparent increase int eh coupler volume as shown in equation 2.12. $E_v$ is the complex temperature transfer function, where R is the length to diameter ratio of the coupler, l is the volume to surface ratio of the coupler, $\alpha_t$ is the thermal diffusivity of the enclosed gas.

$$\begin{aligned} E_V &= 1 - S + D_1 S^2 + \frac{3}{4}\sqrt{\pi} D_2 S^3 \\ S &= \frac{1-j}{2\sqrt{\pi X}} \\ D_1 &= \frac{\pi R^2 + 8R}{\pi(2R+1)^2} \\ D_2 &= \frac{R^3 - 6R^2}{3\sqrt{\pi(2R+1)^3}} \\ X &= \frac{fl^2}{\kappa \alpha_t} \end{aligned} \tag{2.11}$$

$$\Delta_H = \frac{\kappa}{1 + (\kappa - 1)E_V} \tag{2.12}$$

### 2.9.2 High frequency solution

At high frequencies, the effect of viscosity will reduce the effective cross-sectional area of the coupler and increase the effective length of the coupler. The complex expression for the propagation coefficient and the acoustic impedance of are shown in equation 2.13 and 2.14. These losses can be dealt with by an admittance in equation 2.15 added to each microphone admittance.[2] Where $\eta$ is the viscosity of the gas in pascal-seconds and a is the radius of the coupler in meters.

$$\gamma = j\frac{\omega}{c}\left(1+\frac{1-j}{\sqrt{2}}\frac{1}{a}\left(\sqrt{\frac{\eta}{\omega\rho}}+(\kappa-1)\sqrt{\frac{\alpha_t}{\omega}}\right)\right) \tag{2.13}$$

$$Z_{a,0} = \frac{\rho c}{S_0}\left(1+\frac{1-j}{\sqrt{2}}\frac{1}{a}\left(\sqrt{\frac{\eta}{\omega\rho}}+(\kappa-1)\sqrt{\frac{\alpha_t}{\omega}}\right)\right) \tag{2.14}$$

$$\frac{1}{Z_{a,h}} = \frac{S_0}{\rho c}\frac{1+j}{\sqrt{2}}(\kappa-1)\frac{1}{c}\sqrt{\alpha_t\omega} \tag{2.15}$$

# 3
# Methods

This section firstly documents various experimental methods in determining the value of each of the four parameters for the laboratory standard microphone. Then an analytical method of evaluating the interaction between the four parameters combined is introduced.

## 3.1 Front cavity depth

As the conventional contact methods may cause damage to the venerable stretched metallic diaphragm, Non-contact methods, a microscope system is used as the equipment for the optical measurement. Two methods are explored in this sector.

### 3.1.1 Direct method

In the direct method, the front cavity depth is the vertical difference between the value directly measured from the annulus and the diaphragm. Usually, a stable average value can be obtained by measuring 17 points on the diaphragm and 16 points on the annulus. Since there are some higher and lower points on the surface of annulus due to the manufacturing technology, which will cause a slight underestimate of the front cavity depth. However, the front cavity depth does not show any dependence on the applied compressive force provided by the spring-force fixture.

### 3.1.2 Gage block method

The Gage block method uses a gage block placed on the top of the annulus to provide a smoother surface compared to the rough surface of the annulus. The uncertainty of the thickness of the reference gage block considering calibration and temperature variation is at least an order of magnitude smaller than the expanded uncertainties of the front cavity depth. 17 points on the annulus and 8 points on the gage block can obtain a quite stable averaged value.[7]

## 3.2 Total front volume

The following three methods are the most common way to determine the total front volume of the laboratory standard microphone, usually, the nominal value of the front cavity volume is subtracted from the measured total volume to obtain the initial equivalent diaphragm volume before the optimum value is further adjusted with the front cavity volume.

### 3.2.1 Acoustical resonance method

The method uses a three-port coupler, three of the two ports inserted with two microphones as a transmitter-receiver system while the third port firstly is inserted with a standard microphone and then substitute with a plunger, the equivalent volume is calculated by measuring the volumetric changes of the plunger.[2]

### 3.2.2 Couplers method

Several different couplers are used or changing coupler volume by inserting a number of small calibrated rings between the coupler and the microphone under test. The equivalent diaphragm volume is adjusted until the total front volume gave minimal deviations of different couplers at low to medium frequencies. [2]

### 3.2.3 Voltage ratio method

The length of the coupler can be varied with a removable spacer, since the voltage ratio is inversely proportional to the pressure, after some formula deduction[9], the volume of the coupler together with the total front volume of two microphones can be calculated by equation 3.1, where $\beta_0$ to $\beta_2$ are the voltage ratio for different cavity volume and $\Delta V_0$ is the spacer volume. The total front volume can then be determined by interpolation.

$$V = \Delta V_0 \frac{\beta_0}{\beta_1 - \beta_2} \tag{3.1}$$

## 3.3 Loss factor and resonance frequency

### 3.3.1 Laser vibrometer method

A laser vibrometer is used to obtain the frequency response of the diaphragm displacement, one degree-of-freedom vibration model is assumed[11], the solution of the equation of the model is shown in where x is the displacement of the diaphragm $F_0$ is the amplitude of sinusoidal driving force, k is the stiffness of the equivalent vibration system, $\zeta$ is equal to half the loss factor. The response neat the resonance frequency is used to determine loss factor and resonance frequency by least-square fitting.

$$x(f) = \frac{F_0/k}{\sqrt{[1-(f/f_0)^2] + [2\zeta(f/f_0)]^2}} \tag{3.2}$$

### 3.3.2 Electrostatic actuator method

The frequency response is measured by exciting the diaphragm with an electrostatic actuator while terminating the diaphragm with a closed quarter-wavelength tube.

The resonance frequency is then be determined as a frequency of 90° phase change and the loss factor can be calculated by the ratio of the sensitivities at resonance and at low frequencies.[2]

### 3.3.3 Coupler method

The calibration is performed using a number of plane-wave couplers, the resonance frequency and loss factor are adjusted until the same sensitivities are obtained for all couplers.[2]

## 3.4 The application of taguchi method on analysis of relative influence of microphone parameters

The control factors evaluated in this relative significance are front cavity depth, equivalent volume, loss factor and resonance frequency. Since the intersection between the control factors are considered to be negligible and the front cavity volume is significantly influenced by front cavity depth, the front cavity volume is not counted as a new control factor in the parameter investigation. The value chose for the three levels in the relative influence evaluation, are the nominal value on the product data as central value as well as 10% high and low deviation as shown in Table 3.1. In order to minimum the number of experiments under the condition of reaching a conclusion, a degree of freedom as 9 is used in building the orthogonal array as shown in Table 3.2 and 3.3

**Table 3.1:** Microphone parameters value selection

| Microphone parameters | LS1P | | | LS2P | | |
|---|---|---|---|---|---|---|
| Front cavity depth (mm) | 1.76 | 1.95 | 2.14 | 0.45 | 0.50 | 0.55 |
| Equivalent volume ($mm^3$) | 133 | 148 | 163 | 8.4 | 9.3 | 10.2 |
| Loss factor | 0.95 | 1.05 | 1.16 | 0.95 | 1.05 | 1.16 |
| Resonance frquency (kHz) | 7.7 | 8.5 | 9.4 | 21 | 23 | 25 |

**Table 3.2:** The standard orthogonal array of LS1P microphone

| No | Front cavity depth | Equivalent volume | Loss factor | Resonance frequency |
|---|---|---|---|---|
| 1 | 2.14 | 133 | 1.16 | 7.7 |
| 2 | 2.14 | 148 | 1.05 | 8.5 |
| 3 | 2.14 | 163 | 0.95 | 9.4 |
| 4 | 1.95 | 133 | 1.05 | 9.4 |
| 5 | 1.95 | 148 | 0.95 | 7.7 |
| 6 | 1.95 | 163 | 1.16 | 8.5 |
| 7 | 1.76 | 133 | 0.95 | 8.5 |
| 8 | 1.76 | 148 | 1.16 | 9.4 |
| 9 | 1.76 | 163 | 1.05 | 7.7 |

**Table 3.3:** The standard orthogonal array of LS2P microphone

| No | Front cavity depth | Equivalent volume | Loss factor | Resonance frequency |
|---|---|---|---|---|
| 1 | 0.55 | 8.4 | 1.16 | 21 |
| 2 | 0.55 | 9.3 | 1.05 | 23 |
| 3 | 0.55 | 10.2 | 0.95 | 25 |
| 4 | 0.50 | 8.4 | 1.05 | 25 |
| 5 | 0.50 | 9.3 | 0.95 | 21 |
| 6 | 0.50 | 10.2 | 1.16 | 23 |
| 7 | 0.45 | 8.4 | 0.95 | 23 |
| 8 | 0.45 | 9.3 | 1.16 | 25 |
| 9 | 0.45 | 10.2 | 1.05 | 21 |

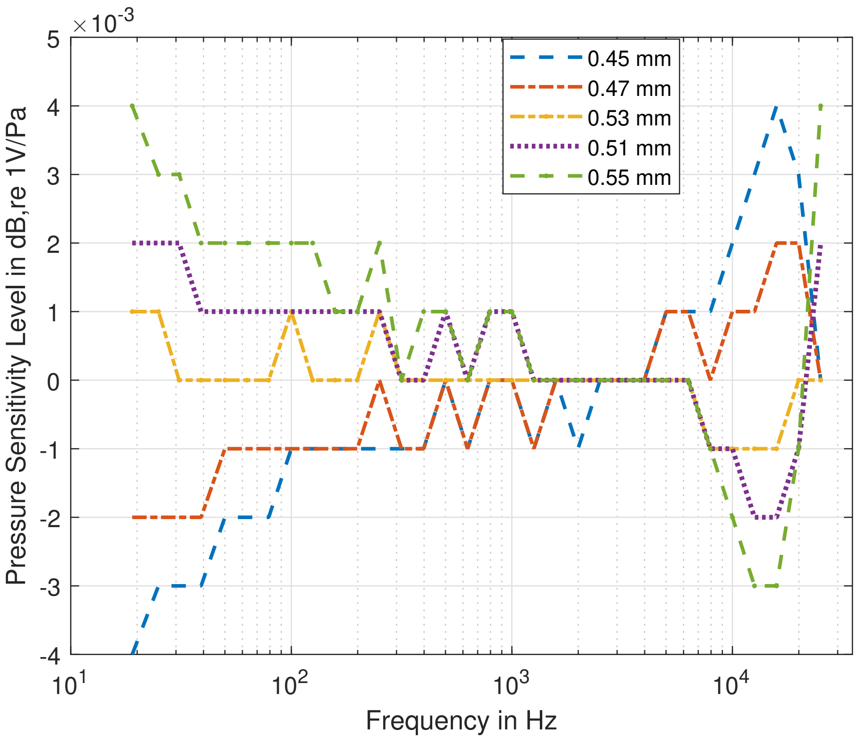
# 4

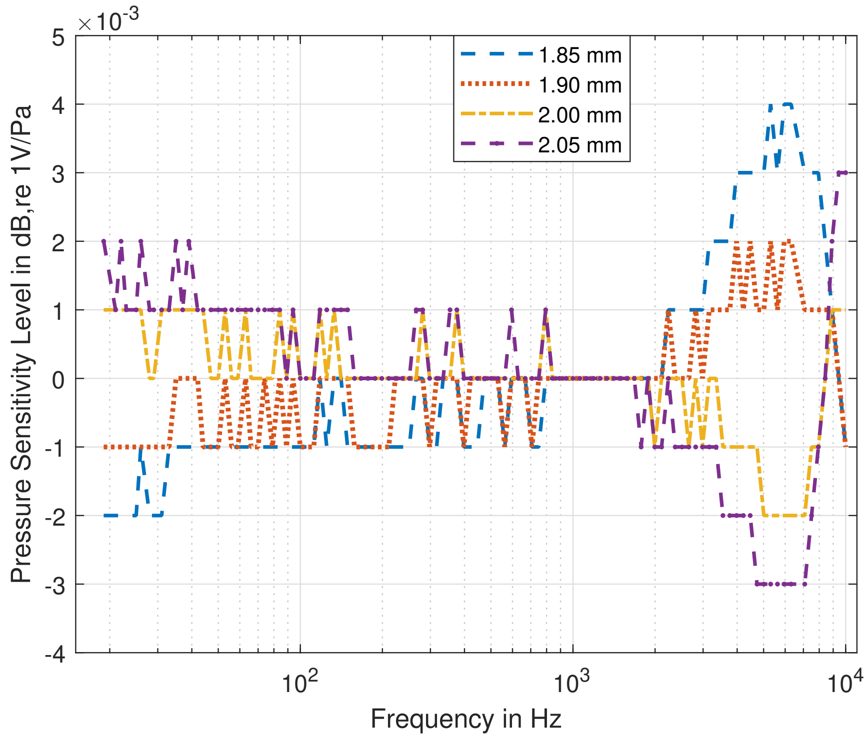
# Results

In this chapter two laboratory standard microphones type B&K 4180 with serial number 1395449 and B&K 4160 with serial number 1144809 is used to demonstrate the influence on the pressure sensitivity level of various microphone parameters. In the frequency response analysis, the ⅓rd octave band is used for the LS2P microphone, and 1⁄12th is the octave band is used for the LS1P microphone.

## 4.1 Front cavity depth

Figure 4.1 shows the pressure sensitivity level difference between the chosen front cavity depth and the nominal center cavity length 0.50 mm and Figure 4.1 shows the pressure sensitivity level difference between the chosen front cavity depth and the nominal center cavity length 1.95 mm. Curves are obtained by using the chosen value to subtract the nominal value. Figure 4.1 shows the phase shift of the reciprocity calibration result.





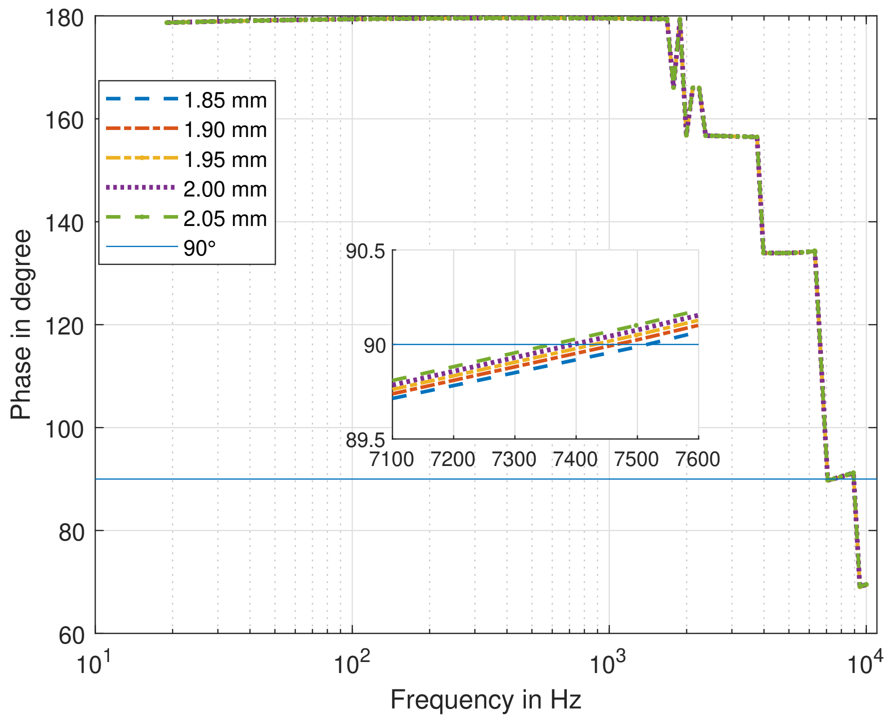




Figure 4.1 and 4.2 are the comparison of front cavity depth in expanded uncertainty with direct and gage block methods as with the nominal value which is obtained from the experiment results [7]. The cavity depth which can be read from the figure are 0.465 ± 0.004 mm, 0.467 ± 0.003 mm, and 0.5 ± 0.05 mm for LS2P microphone and 1.96 ± 0.003 mm, 1.96 ± 0.002 mm and 1.95 ± 0.1 mm for LS1P microphone.

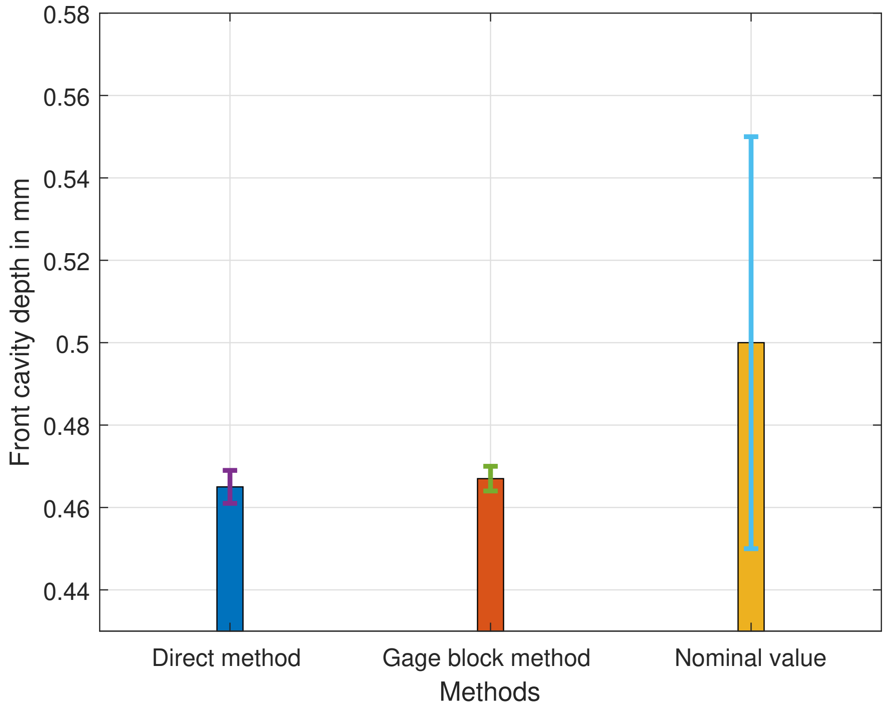



**Figure 4.1:** Front cavity value and the deviation by using different methods for LS2P

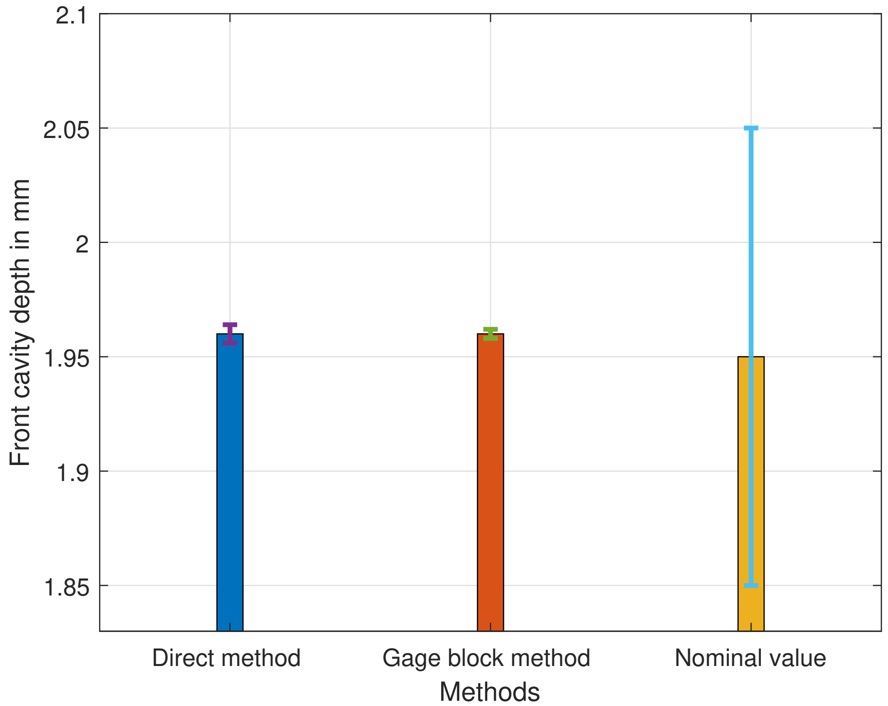



**Figure 4.2:** Front cavity value and the deviation by using different methods for LS1P

The uncertainty component influences on the final pressure sensitivity level is shown in Figure 4.3. The curves are the differences between the largest and smallest possible limitation.

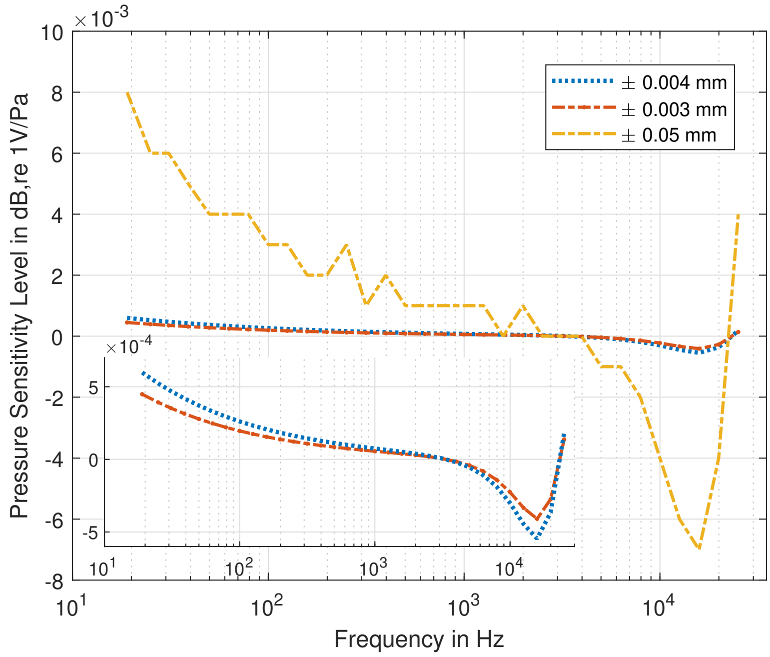



**Figure 4.3:** The maximum error of the pressure sensitivity level with three uncertainty limitations for LS2P microphone

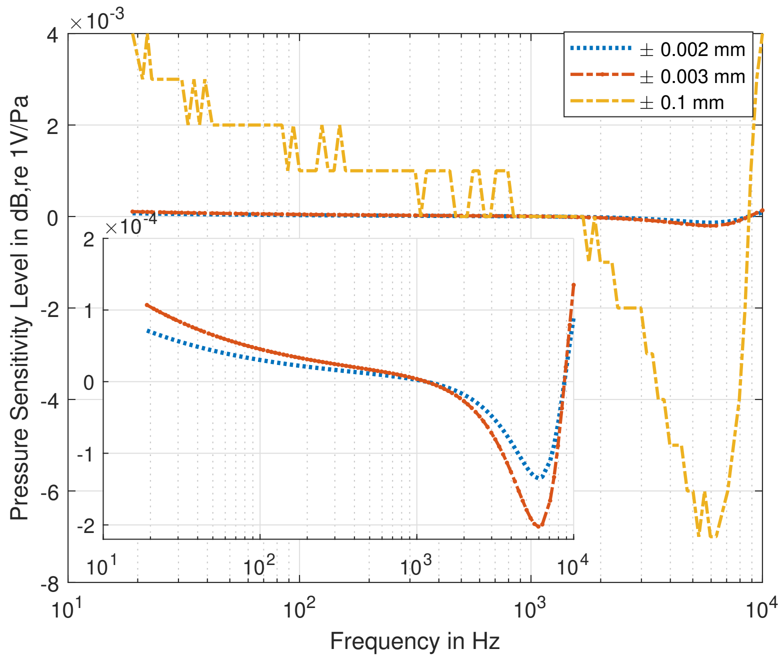



**Figure 4.4:** The maximum error of the pressure sensitivity level with three uncertainty limitations for LS1P microphone

## 4.2 Equivalent volume

Figure 4.5 and 4.6 shows the pressure sensitivity level differences between the chosen equivalent volume and the nominal volume 9.2 $mm^3$ for LS2P microphone and 148 $mm^3$ for LS1P microphone. Curves are obtained by using the chosen value to subtract the nominal value. Figure 4.7 shows the phase shift of the reciprocity calibration system.

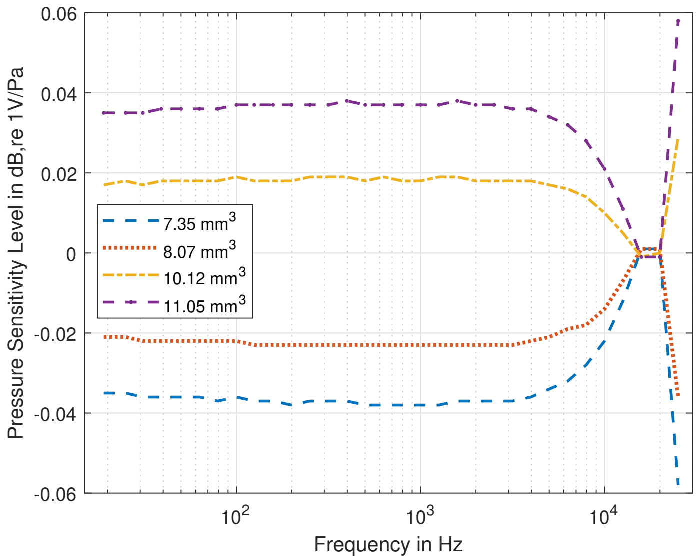



**Figure 4.5:** Pressure sensitivity level difference between the usage of chosen equivalent volume and the nominal value for LS2P microphone

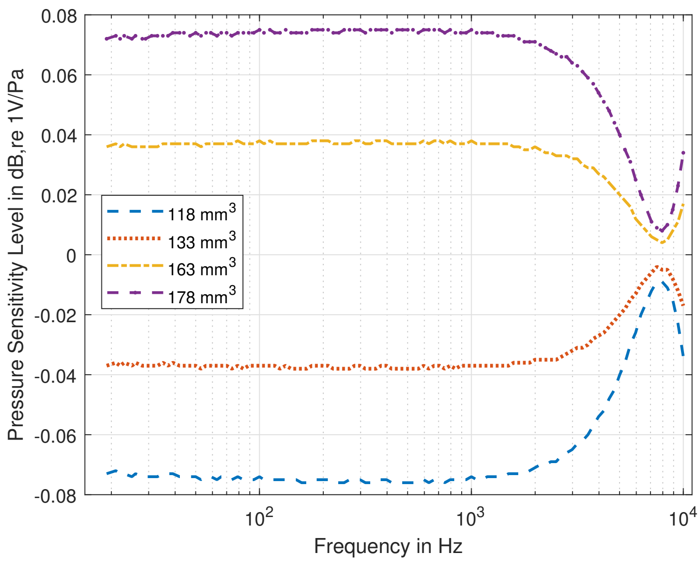



**Figure 4.6:** Pressure sensitivity level difference between the usage of chosen equivalent volume and the nominal value for LS1P microphone

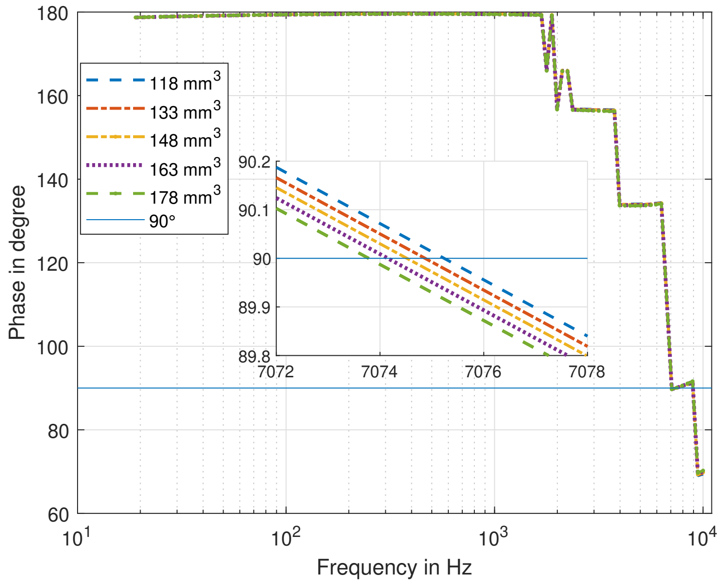



**Figure 4.7:** The phase of the pressure sensitivity using different equivalent volume for LS1P

Figure 4.8 and 4.9 are the comparison of equivalent volume in expanded uncertainty with couplers and acoustical resonance methods as with as the nominal value which are obtained from the experiment results [10]. The equivalent volume which can be read from the figure are $9.3 \pm 0.32\ mm^3$, $9.3 \pm 0.31\ mm^3$ and $9.2 \pm 1.85\ mm^3$ for LS2P microphone and $131.9 \pm 2.62\ mm^3$, $131.9 \pm 2.52\ mm^3$ and $148 \pm 30\ mm^3$ for LS1P microphone.

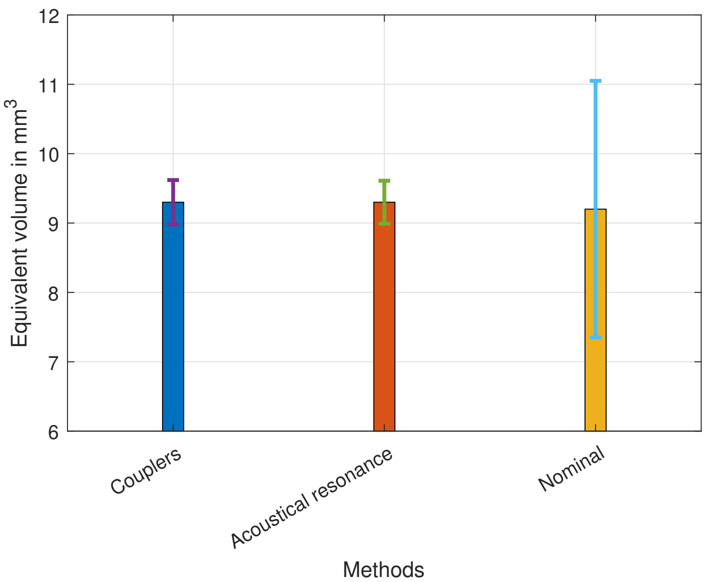



**Figure 4.8:** Equivalent volume value and the deviation by using different methods for LS2P

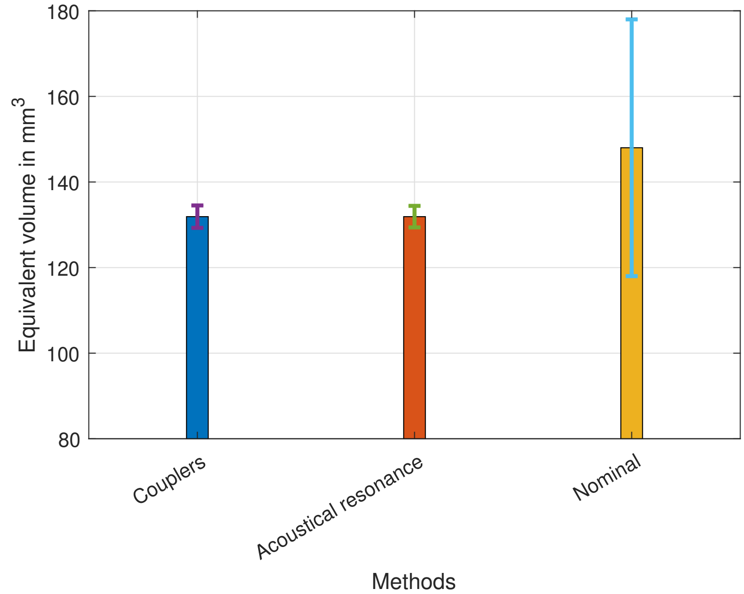



**Figure 4.9:** Equivalent volume value and the deviation by using different methods for LS1P

The influences of the uncertainty component on the final pressure sensitivity level are shown in Figure 4.10 and 4.11. The curves are the differences between the largest and smallest possible limitation.

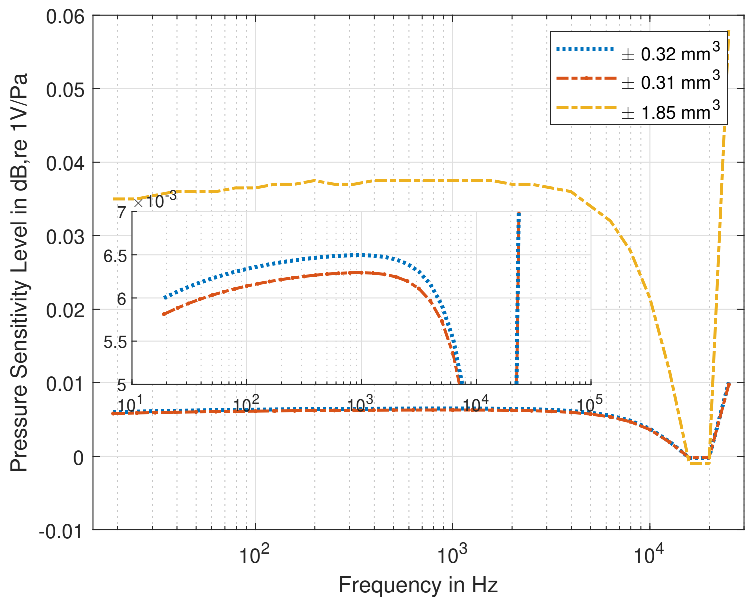



**Figure 4.10:** The maximum error of the pressure sensitivity level with three uncertainty limitations for LS2P microphone

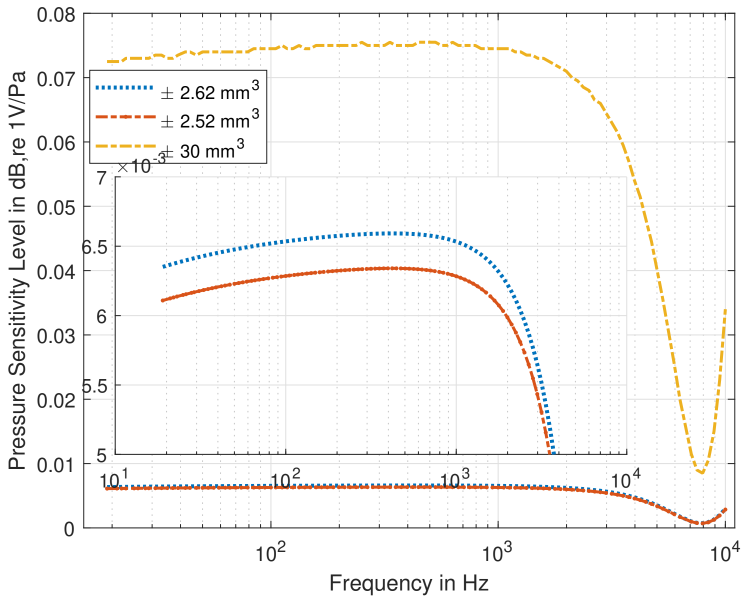



**Figure 4.11:** The maximum error of the pressure sensitivity level with three uncertainty limitations for LS1P microphone

## 4.3 Loss factor

Figure 4.12 and 4.13 shows the pressure sensitivity level differences between the chosen loss factor value and the nominal value 1.05 for both microphone type. Curves are obtained by using the chosen value to subtract the nominal value. Figure 4.14 shows the phase shift of the reciprocity calibration system.

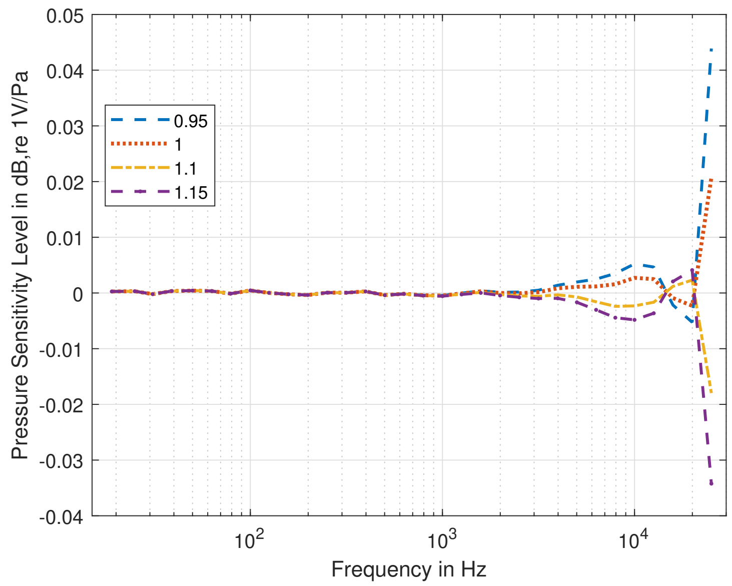



**Figure 4.12:** Pressure sensitivity level difference between the usage of chosen loss factor and the nominal value for LS2P microphone

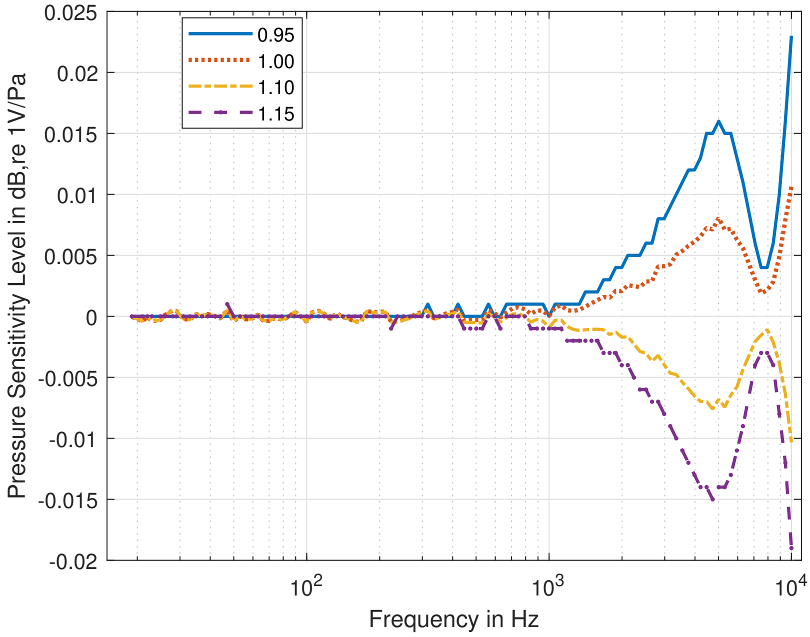



**Figure 4.13:** Pressure sensitivity level difference between the usage of chosen loss factor and the nominal value for LS1P microphone

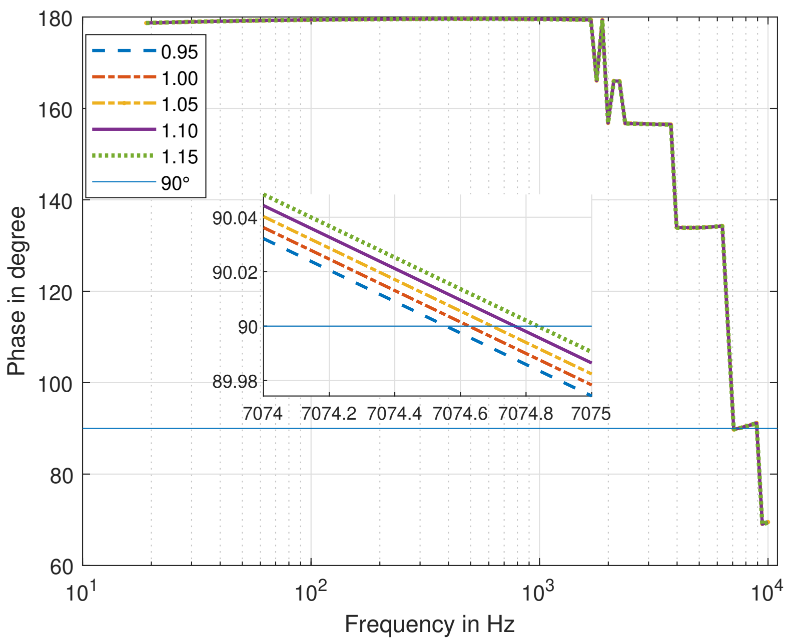



**Figure 4.14:** The phase of the pressure sensitivity using different loss factor for LS1P

Figure 4.15 is the comparison of resonance frequency in expanded uncertainty with the electrostatic actuator, laser vibrometer, couplers as with the nominal value which is obtained from the experiment results [12]. Figure 4.16 is the comparison of resonance frequency in expanded uncertainty with the couplers method and nominal value which are obtained from the experiment results [13]. The loss factor which can be read from the figure are 1.03 ± 0.02, 1.04 ± 0.0085,1.08 ± 0.1 and 0.15 ± 0.15 for LS2P microphone and 1.05 ± 0.02 and 1.05 ± 0.05 for LS1P microphone.

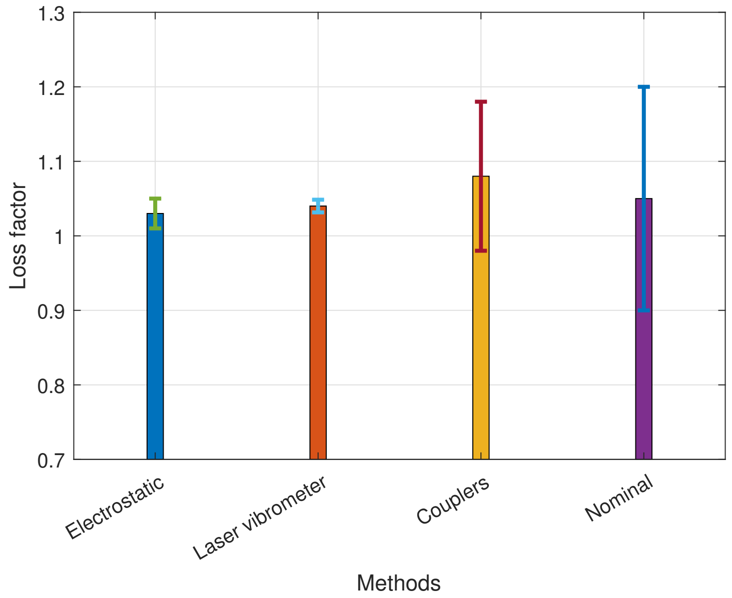



**Figure 4.15:** Loss factor value and the deviation by using different methods for LS2P

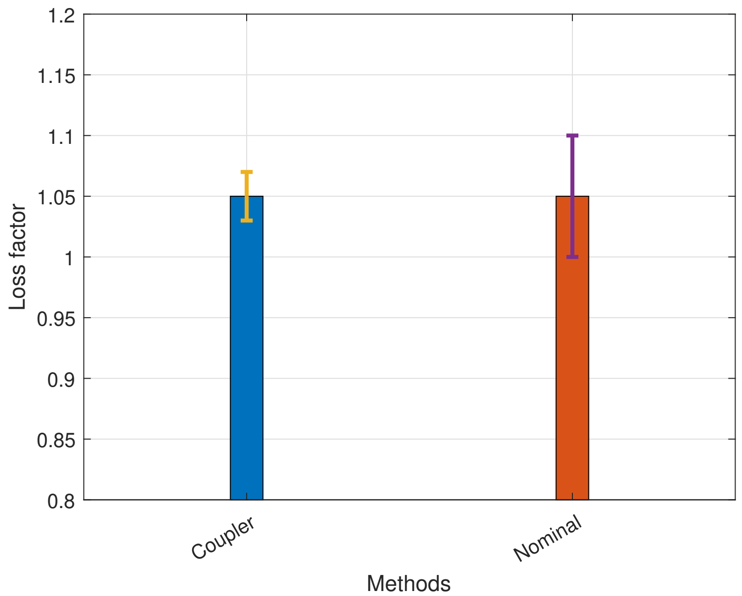



**Figure 4.16:** Loss factor value and the deviation by using different methods for LS1P

The influences of the uncertainty component on the final pressure sensitivity level are shown in Figure 4.17 and 4.18. The curves are the differences between the largest and smallest possible limitation.

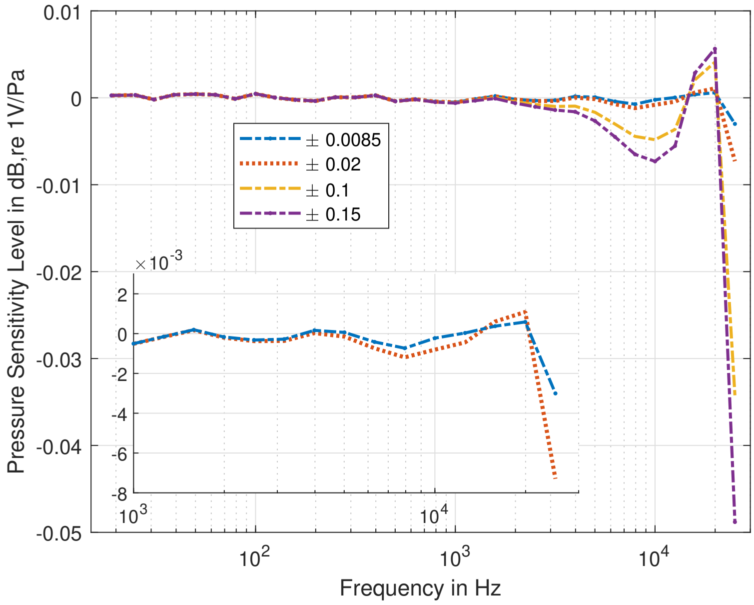



**Figure 4.17:** The maximum error of the pressure sensitivity level with different uncertainty limitations for LS2P microphone

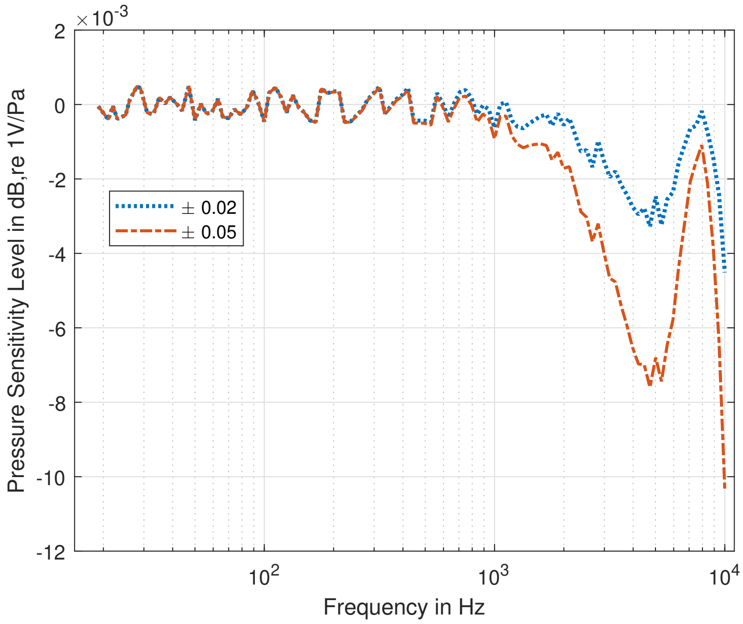



**Figure 4.18:** The maximum error of the pressure sensitivity level with different uncertainty limitations for LS1P microphone

## 4.4 Resonance frequency

Figure 4.19 and 4.20 shows the pressure sensitivity level differences between the chosen resonance frequency value and the nominal value 22 kHz for LS2P microphone and 8.4 kHz for LS1P microphone . Curves are obtained by using the chosen value to subtract the nominal value. Figure 4.21 shows the phase shift of the reciprocity calibration system.

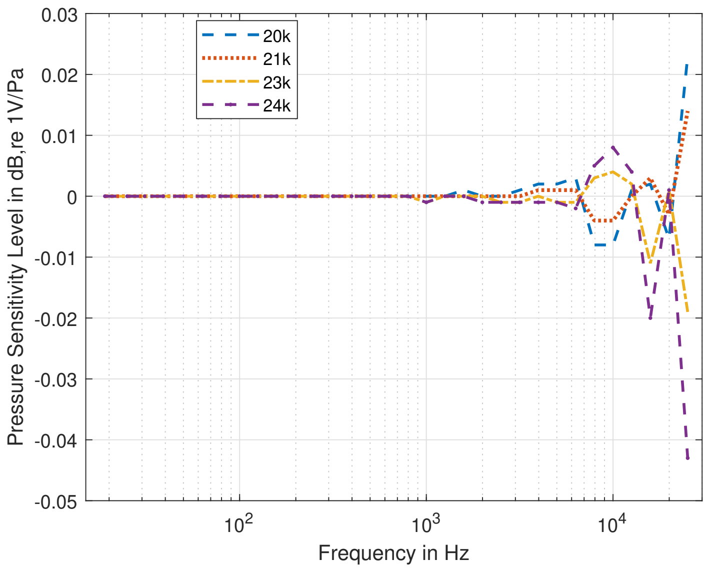



**Figure 4.19:** Pressure sensitivity level difference between the usage of chosen resonance frequency and the nominal value for LS2P microphone

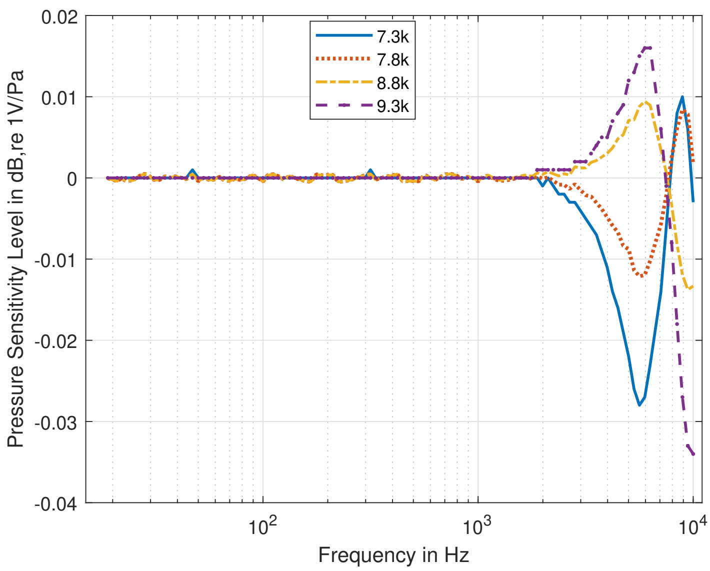



**Figure 4.20:** Pressure sensitivity level difference between the usage of chosen resonance frequency and the nominal value for LS1P microphone

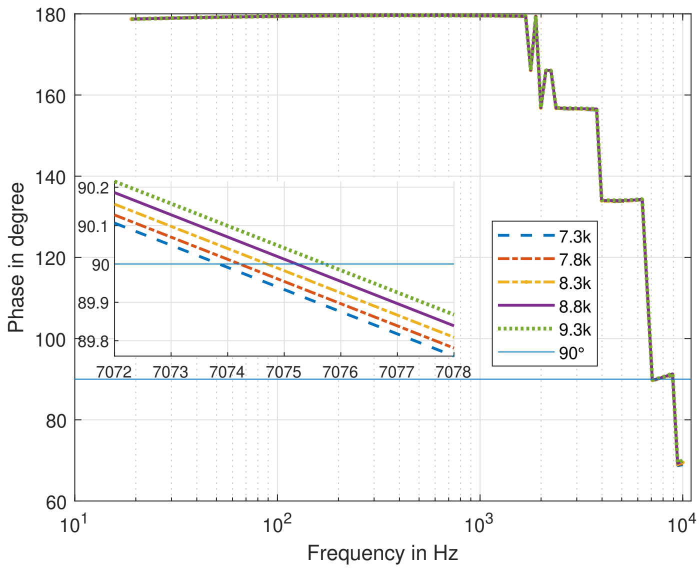



**Figure 4.21:** The phase of the pressure sensitivity using different resonance frequency for LS1P

Figure 4.22 is the comparison of resonance frequency in expanded uncertainty with the electrostatic actuator, laser vibrometer as well as the nominal value which are obtained from the experiment results [12]. Figure 4.23 is the comparison of resonance frequency in expanded uncertainty with the couplers method and nominal value which are obtained from the experiment results [13]. Figure The resonance frequency which can be read from the figure are 20500 $\pm$ 138 Hz, 23500 $\pm$ 1000 Hz and 22000 $\pm$ 2000 Hz for LS2P microphone and 8300 $\pm$ 300 Hz and 8400 $\pm$ 1000 Hz for LS1P microphone.

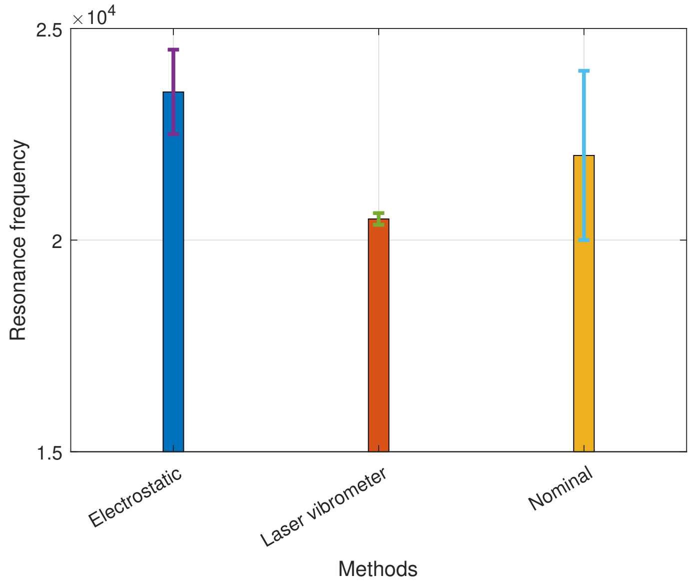



**Figure 4.22:** resonance frequency value and the deviation by using different methods for LS2P

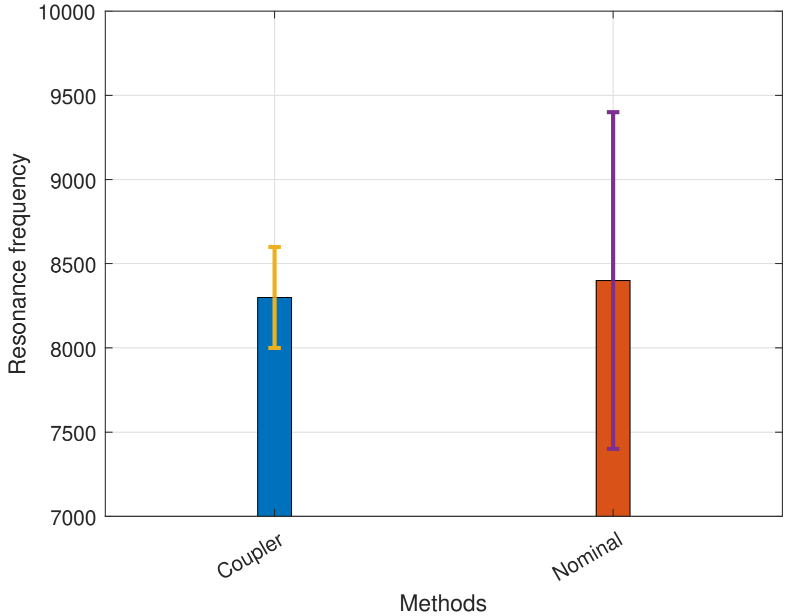



**Figure 4.23:** resonance frequency value and the deviation by using different methods for LS1P

The influences of the uncertainty component on the final pressure sensitivity level are shown in Figure 4.24 and 4.25. The curves are the differences between the largest and smallest possible limitation.

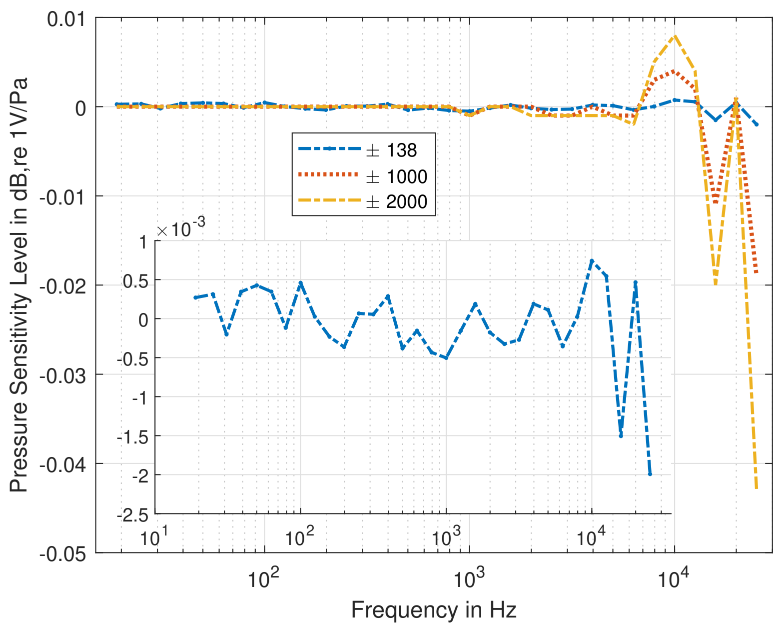



**Figure 4.24:** The maximum error of the pressure sensitivity level with different uncertainty limitations for LS2P microphone

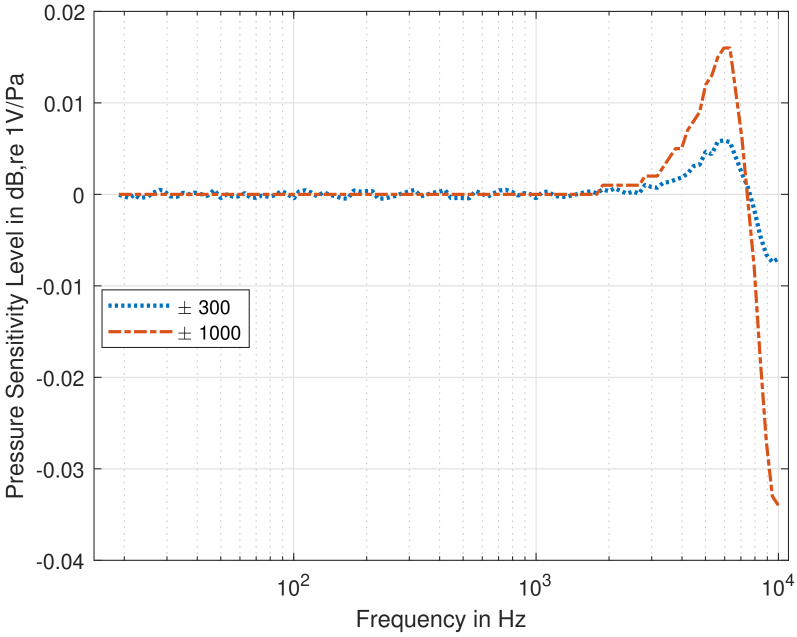



**Figure 4.25:** The maximum error of the pressure sensitivity level with different uncertainty limitations for LS1P microphone

Figure 4.26 and 4.27 show the averaged effect on the pressure sensitivity level by different parameters at three levels for LS2P microphone at 250 Hz and 20 kHz respectively and Figure 4.28 and Figure 4.29 are the effect result plots for LS1P microphone at 250 Hz and 8.4 kHz. Each value at the level for a certain parameter is calculated by averaging over the results for three experiments as shown in Table 3.2 and Table 3.3. Ldepth stands for front cavity volume, Veq stands for equivalent volume and $f_0$ is the resonance frequency.

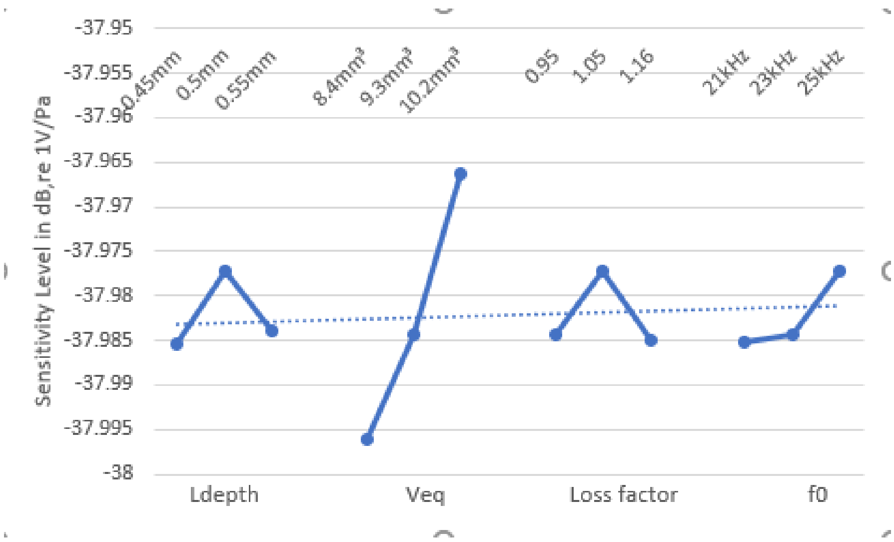



**Figure 4.26:** The average sensitivity at three levels for LS2P microphone at 250 Hz

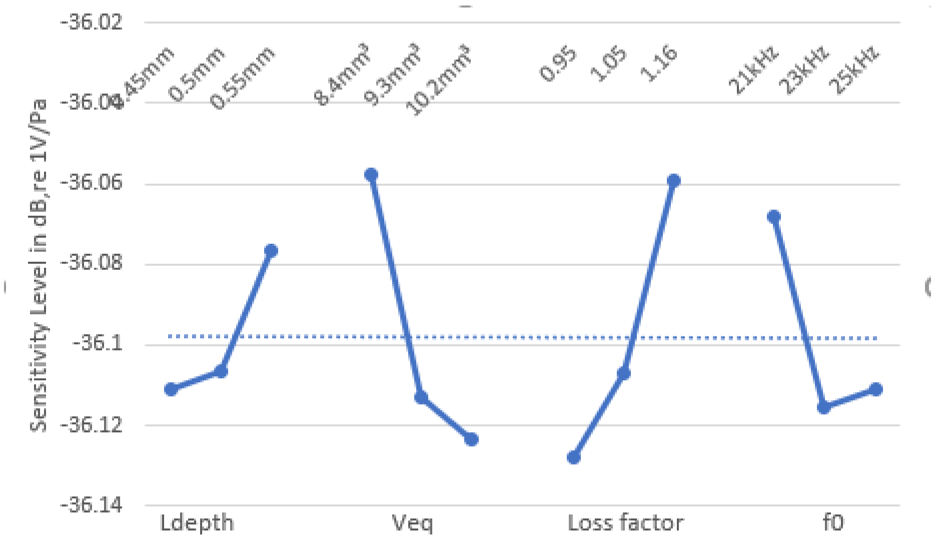



**Figure 4.27:** The average sensitivity at three levels for LS2P microphone at 20 kHz

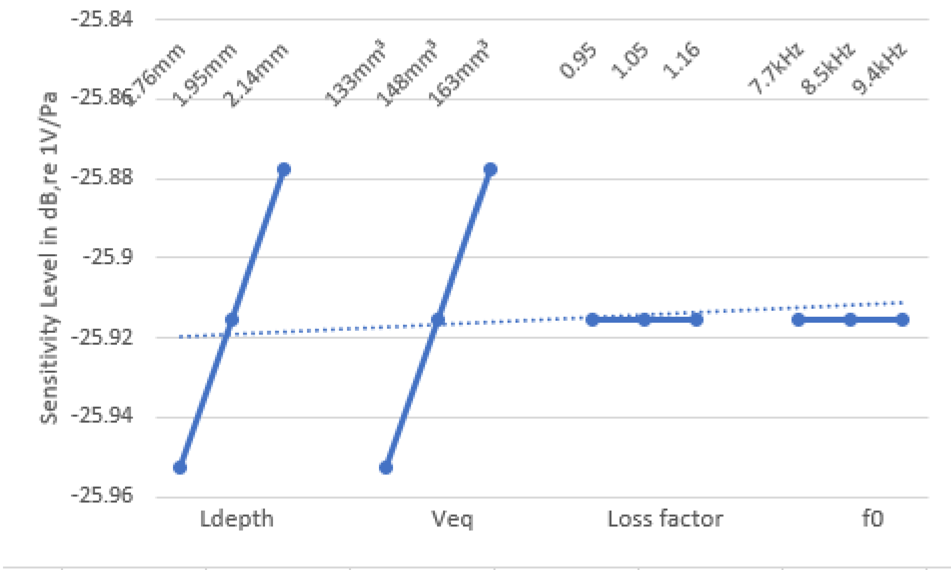



**Figure 4.28:** The average sensitivity at three levels for LS1P microphone at 250 Hz

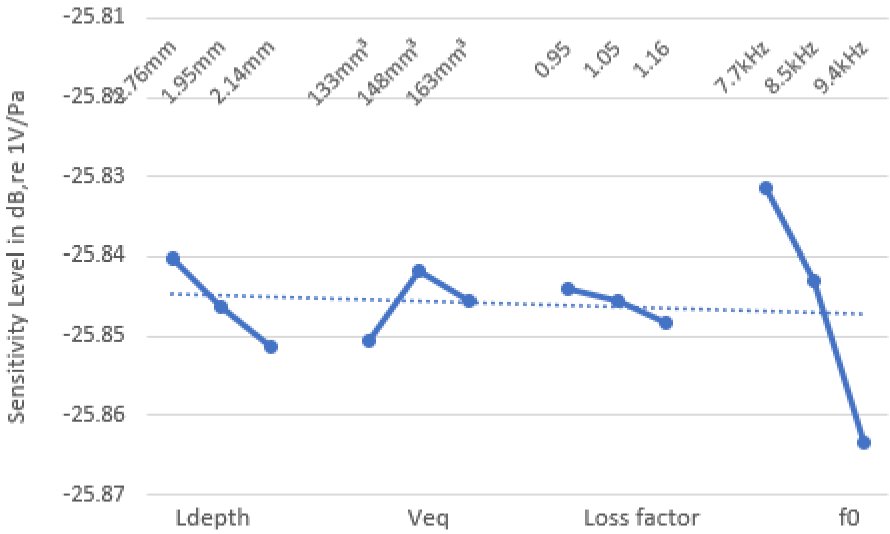



**Figure 4.29:** The average sensitivity at three levels for LS1P microphone at 8400 Hz

Table 4.3 to Table 4.4 list the results of analysis of variance for LS2P microphone at 250 Hz and 20 kHz as well as LS1P microphone at 250 Hz and 8400 Hz. SSB stands for sum of squares between groups, df represents degree of freedom, MS calculates the mean square,F is the F-ratio and P is the percentage contribution.

**Table 4.1:** ANOVA result for LS2P microphone at 250 Hz

| Parameters | SSB | df | MS | F | P |
|---|---|---|---|---|---|
| cavity depth | 0.000114 | 2 | 5.71E-05 | 0.216996 | 1.7% |
| equivalent volume | 0.001349 | 2 | 0.000675 | 11.79432 | 94.8% |
| loss factor | 0.000114 | 2 | 5.69E-05 | 0.216113 | 1.7% |
| resonance frequency | 0.000115 | 2 | 5.77E-05 | 0.219335 | 2% |

**Table 4.2:** ANOVA result for LS2P microphone at 20 kHz

| Parameters | SSB | df | MS | F | P |
|---|---|---|---|---|---|
| cavity depth | 0.002071 | 2 | 0.001036 | 0.326634 | 7.5% |
| equivalent volume | 0.007492 | 2 | 0.003746 | 1.652088 | 38.1% |
| loss factor | 0.007401 | 2 | 0.0037 | 1.621099 | 37.4% |
| resonance frequency | 0.004132 | 2 | 0.002066 | 0.730788 | 17% |

**Table 4.3:** ANOVA result for LS1P microphone at 250 Hz

| Parameters | SSB | df | MS | F | P |
|---|---|---|---|---|---|
| cavity depth | 0.008438 | 2 | 0.004219 | 5385.644 | 49.8% |
| equivalent volume | 0.008438 | 2 | 0.004219 | 5385.644 | 49.8% |
| loss factor | 1.56E-08 | 2 | 7.78E-09 | 5.53E-06 | 0.4% |
| resonance frequency | 2.22E-09 | 2 | 1.11E-09 | 7.9E-07 | |

**Table 4.4:** ANOVA result for LS1P microphone at 8.4 kHz

| Parameters | SSB | df | MS | F | P |
|---|---|---|---|---|---|
| cavity depth | 0.000184 | 2 | 9.2E-05 | 0.320023 | 2.1% |
| equivalent volume | 0.000116 | 2 | 5.79E-05 | 0.193682 | 1.3% |
| loss factor | 2.77E-05 | 2 | 1.38E-05 | 0.044152 | 0.3% |
| resonance frequency | 0.001581 | 2 | 0.000791 | 14.48855 | 96% |

# 5

# Analysis

## 5.1 Front cavity depth

As can be seen in Figure 4.1 and Figure 4.1. For LS2P microphone, at frequencies lower than 6309 Hz and 3981 Hz, for cavity depth chosen values bigger and smaller than the nominal values respectively, larger cavity depth value will cause higher pressure sensitivities, however, the case will be the opposite when frequencies exceed the critical frequency. In frequency ranges aside from the resonance frequency and low-frequency range, the differences in pressure sensitivity level fall within 0.001 dB. There are also two convergence points can be discovered at around 20 kHz for cavity depth chosen values bigger than the nominal values, and 25 kHz for smaller values. For LS1P microphone, at frequencies lower than around 1700 Hz and 2113 Hz respectively, for cavity depth chosen values bigger and smaller than the nominal values, larger cavity depth value will cause higher pressure sensitivities, however, the case will be the opposite when frequencies exceed the critical frequency. The highest deviation can be noticed to reach 0.004 dB for both microphone types. In Figure 4.1 the phase begins to change to 90° from 1678 Hz and the system resonance frequencies appear around 7500 Hz. The longer the cavity depth the higher the resonance frequency it will shift to.

## 5.2 Equivalent volume

As can be seen in Figure 4.5 and Figure 4.6, the sensitivity curve is quite flat at low and middle frequencies until at a certain frequency the curves start to fall until almost reach 0 dB around the resonance frequency. The critical frequency is 3900 Hz for the LS2P microphone and 1500 Hz for the LS1P microphone. The curves start increasing rapidly and surpass the original steady value read at lower frequencies and go up to around 0.06 dB the maximum for LS2P microphone. For the LS1P microphone, the curves increase gently to a level much smaller than the value at lower frequencies. Figure 4.7 shows that the higher equivalent volume will result in a lower resonance frequency.

## 5.3 Loss factor

In Figure 4.12 and Figure 4.13 , the variation of loss factor shows little influence on the sensitivity result at low and middle frequencies for both microphone types. A bigger difference appears from 5000 Hz for the LS2P microphone and 1000 Hz for LS1P microphone, the larger the loss factor deviation from the nominal value, the larger error will be noticed in the sensitivity result. For the LS2P microphone, the bigger loss factor will get a smaller sensitivity level, except for the frequency range from around 14500 Hz to 20000 Hz, where the case is the opposite. There are a dip and a bump at around 10000 Hz and 19000 Hz, where the highest deviation of 0.005 dB can be noticed. A sharp steep appears after the peak and causes an error of 0.04 dB at 25000 Hz. For the LS1P microphone, the bigger the loss factor value, the smaller the sensitivity level will be obtained for the whole frequency range. The changes of loss factor have a larger influence on the dip than the bump, the highest deviation of 0.016 dB can be found around 5000 Hz, however, at the frequency of 8000 Hz, the highest deviation for the peak is only 0.004 dB. A sharp steep can also be observed and lead to an error of 0.023 at 10000 Hz. Figure 4.14 shows the influence of loss factor on phase shift. The graph starts a phase shift at around 1700 Hz and the resonance frequency shifts to higher frequencies when the loss factor value increasing.

## 5.4 Resonance frequency

As shown in Figure 4.19 and Figure 4.20, there is no significant difference in the pressure sensitivity level in the low-frequency range with variant resonance frequency value. For the LS2P microphone, a noticeable deviation starts from around 800 Hz. There are two peaks around 10000 Hz and 20000 Hz, where the larger resonance frequency will cause a larger pressure sensitivity level. The error can reach to 0.007 dB at the two bumps and 0.02 dB in the dip. The biggest error 0.04 dB appears at 25000 Hz. For LS1P, the changes of resonance frequency begin to have a significant impact on the pressure sensitivity results after 2000 Hz, then a peak appears at around 6000 Hz and can reach the bigger error of 0.028 dB, the larger deviation value from the nominal value, the larger error it will cause. Figure 4.21 shows the resonance frequency will shift to higher frequencies, which is consistent with the input resonance frequency.

## 5.5 Relative influence of microphone parameters on reciprocity calibration

Figure 4.26 and Table 4.1 show that for the LS2P microphone at 250 Hz, the equivalent volume influences the result most, which constitutes 94.8% of the relative significance . The other three parameters have an almost equal impact on sensitivity. At frequency 20 kHz, which can be observed from Figure 4.27 and Table 4.2 equivalent volume and loss factor dominate the influences, which take up to around 38% contribution each, the cavity depth has the least impact for LS2P microphone at this frequency. Figure 4.28 and Table 4.3 describe that front cavity depth and equivalent volume have a strong equal effect on the sensitivity, however, loss factor and resonance frequency have almost no impact on the final result at 250 Hz for

LS1P microphone. When the frequency goes up to 8400 Hz, the resonance frequency appears to be the most influential factor as implied in Figure 4.29 and Table 4.4, a 96% percentage contribution can be read.

# 6

# Uncertainty

In this chapter, the uncertainty of various experimental methods of each of the parameters is analyzed first, then the uncertainty budgets for the four parameters together are generated by choosing the optimal combinations.

## 6.1 Front cavity depth

The methods of choice in measuring front cavity depth will have an impact on the uncertainty of pressure sensitivity. The nominal depth will cause large deviations in calculating the pressure sensitivity level, especially in high frequencies. An example of a type LS2P microphone with a tolerance error of $\pm 0.1$ mm will lead to $\pm 0.8$ dB error in pressure sensitivity level at 25 kHz. The permissible microphone front cavity depth as stated is 1.95 mm $\pm$ 0.1 mm for LS1P and 0.5 mm $\pm$ 0.05 mm for LS2P[7]. Figure 4.1 and Figure 4.2 show that, the gage block method has narrower expanded uncertainty compared with direct methods. In Figure 4.3, the nominal uncertainty of $\pm 0.05$ mm will cause about 0.007 dB error in the results at the resonance frequency, however, by determining the individual microphone front cavity depth, the error can reduce to 0.0004 dB. The error difference between the two measurement methods can go up to 0.0001 dB at low frequencies as well as around the resonance frequency. Both methods use all most the same equipment except affordable gage blocks, however, the gage block method is more time saving and with a more accurate result, it can be chosen as an optimum method.

## 6.2 Equivalent volume

It can be seen clearly from Figure 4.8 and Figure 4.9, the acoustical resonance method has a slightly narrower error bar than the couplers method for both LS1P and LS2P microphone. In figure 4.10, the maximum error is around 0.037 dB for the nominal uncertainty and 0.006 dB for the other two different methods. The maximum error for the coupler method is 0.0002 dB larger than the acoustical resonance method in low and middle-frequency range. There is almost no difference between methods of chosen at around resonance frequency for LS2P microphone. In figure 4.11, the pressure sensitivity level is about 0.075 dB for the nominal uncertainty and about 0.006 dB for the other methods, the difference between the two methods of chosen can reach a deviation about 0.00025 dB in the flat frequency range. At the resonance frequency, the equivalent volume determined by experiment methods still has a smaller error which is about 0.0007 dB than the nominal value. The acoustical resonance methods can generate a slightly accurate result and it costs less time to determine the value of the total front volume. But the coupler method takes the advantage that an extra three-port coupler is omitted.

## 6.3 Loss factor

Compared in Figure 4.15, the laser vibrometer method has the narrowest uncertainty, deviation of the coupler method is slightly better than the nominal value. The loss factor influences the uncertainty most around the resonance and high frequency. In Figure 4.17. By using electrostatic and laser vibrometer methods, the maximum error of the pressure sensitivity level can reduce from around 0.04 dB to 0.005 dB. Around resonance frequency, a laser vibrometer, an electrostatic actuator, and couplers method will cause about 0.0007 dB, 0.01 dB, and 0.004 dB error respectively. In Figure 4.18, the uncertainty is around 0.0004 dB in low and middle frequency range. By using the coupler method, the deviation decreased from 0.0076 dB to 0.003 dB at around 5300 Hz,

## 6.4 Resonance frequency

For the LS2P microphone, compared in Figure 4.22, the laser vibrometer method has the narrowest uncertainty. As shown in Figure 4.24, around the resonance frequency range, the two methods, as well as the nominal value, have an average uncertainty of 0.001 dB, 0.01 dB, and 0.02 dB respectively. For the LS1P microphone, as can be seen from Figure 4.23 and 4.25, the couplers method can minimize the uncertainty to 1/3 of the nominal value, the error in the pressure sensitivity level can be decreased from 0.03 dB to 0.007 dB. Compared with the three methods. For the laser vibrometer method, the repeatability is highly feasible. Due to the influence of the radiation impedance of the diaphragm, the electrostatic actuator method can only get a slightly lower resonance frequency. With the inclusion of the reciprocity calibration in the coupler method, the calibration will usually cost one hour per coupler.

## 6.5 Uncertainty budgets

The uncertainty budgets select the most accurate method for each parameter to obtain the overall uncertainty for microphone characteristics only. Table 6.1 is the uncertainty budget for LS2P microphone, gage block method is chosen for front cavity depth, acoustical resonance method is used for equivalent volume, the loss factor and resonance frequency are determined by a laser vibrometer Table 6.2 is the uncertainty budget for LS1P microphone, gage block method is chosen for front cavity depth, acoustical resonance method is used for equivalent volume, the loss factor and resonance frequency are determined by the couplers method.

**Table 6.1:** Uncertainty budget for LS2P microphone

| Components | | | | | | | | Frequency(Hz) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rectangular distribution(B type) | 19 | 31 | 63 | 125 | 251 | 501 | 1000 | 1995 | 3981 | 6309 | 7943 | 10000 | 12589 | 15848 | 19952 | 25118 |
| Front cavity depth | 0.000448 | 0.000353 | 0.000247 | 0.000175 | 0.000122 | 8.43E-05 | 5.59E-05 | 2.94E-05 | -1.46E-05 | -8.14E-05 | -0.00014 | -0.00023 | -0.00033 | -0.00041 | -0.00027 | 0.000137 |
| Equivalent volume | 0.035 | 0.0355 | 0.036 | 0.037 | 0.037 | 0.0375 | 0.0375 | 0.037 | 0.036 | 0.032 | 0.028 | 0.0215 | 0.0115 | -0.001 | -0.001 | 0.058 |
| Loss factor | 0.000269 | -0.0002 | 0.000344 | 2.31E-05 | 6.19E-05 | -0.00039 | -0.0005 | -0.00017 | 0.000163 | -0.00042 | -0.00073 | -0.00023 | 3.05E-05 | 0.000374 | 0.000585 | -0.003 |
| Resonance frequency | 0.00027 | -0.0002 | 0.000346 | 2.59E-05 | 6.65E-05 | -0.00038 | -0.0005 | -0.00018 | 0.000189 | -0.00036 | 2.37E-05 | 0.000741 | 0.000544 | -0.00151 | 0.000465 | -0.00199 |
| Combined standard uncertainty | 0.035987 | 0.035447 | 0.036937 | 0.037224 | 0.03725 | 0.036816 | 0.036547 | 0.036683 | 0.036337 | 0.031145 | 0.027151 | 0.021788 | 0.01174 | -0.00254 | -0.00022 | 0.05314 |
| Expanded uncertainty(k=2) | | 0.070893 | 0.073874 | 0.074447 | 0.074501 | 0.073633 | 0.073095 | 0.073366 | 0.072674 | 0.062289 | 0.054301 | 0.043575 | 0.023481 | -0.00508 | -0.00045 | 0.106281 |

**Table 6.2:** Uncertainty budget for LS1P microphone

| Components | Frequency(Hz) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rectangular distribution(B type) | 19 | 25 | 31 | 63 | 125 | 251 | 501 | 1000 | 1995 | 2511 | 3162 | 3981 | 5011 | 6309 | 7943 | 10000 |
| Front cavity depth | 7.13E-05 | 6.21E-05 | 5.56E-05 | 3.85E-05 | 2.69E-05 | 1.83E-05 | 1.12E-05 | 2.52E-06 | -1.81E-05 | -3.24E-05 | -5.37E-05 | -8.39E-05 | -0.00012 | -0.00013 | -5.97E-05 | 9.00E-05 |
| Equivalent volume | 0.006109 | 0.006149 | 0.006177 | 0.00625 | 0.006299 | 0.006331 | 0.006339 | 0.006284 | 0.005988 | 0.005734 | 0.005305 | 0.004575 | 0.003368 | 0.001696 | 0.000709 | 0.002851 |
| Loss factor | -4.72E-05 | -0.00028 | -0.00022 | 0.00015 | -0.00022 | -0.0003 | -0.00044 | -0.00063 | -0.00055 | -0.00123 | -0.00195 | -0.00276 | -0.00247 | -0.00155 | -0.00018 | -0.00451 |
| Resonance frequency | -4.89E-05 | -0.00028 | -0.00023 | 0.000148 | -0.00022 | -0.00029 | -0.0004 | -0.00043 | 0.00035 | 0.000314 | 0.000723 | 0.00184 | 0.004674 | 0.005713 | -0.00165 | -0.00701 |
| Combined standard uncertainty | 6.08E-03 | 5.64E-03 | 5.78E-03 | 6.59E-03 | 5.89E-03 | 5.75E-03 | 5.52E-03 | 5.23E-03 | 5.77E-03 | 4.79E-03 | 4.02E-03 | 3.57E-03 | 5.45E-03 | 5.73E-03 | -1.17E-03 | -8.58E-03 |
| Expanded uncertainty(k=2) | 1.22E-02 | 1.13E-02 | 1.16E-02 | 1.32E-02 | 1.18E-02 | 1.15E-02 | 1.10E-02 | 1.05E-02 | 1.15E-02 | 9.58E-03 | 8.05E-03 | 7.15E-03 | 1.09E-02 | 1.15E-02 | -2.35E-03 | -1.72E-02 |

# 7
# Refinement

In the previous work, the 'broad-band' solution is used for the whole frequency range. However, according to IEC 61094-2, there are two different correction factors applied to low and high-frequency situations respectively in heat conduction and viscous losses correction to obtain a more accurate result. The sound pressure is the same at any point inside the coupler and only be assumed when the coupler dimension is much smaller than the wavelength,250 Hz is set as a boundary of low and high frequency. As can be seen from Figure 7.1 and Figure 7.2,below 250 Hz, the new system has a slightly low pressure sensitivity level. For the LS2P microphone, the difference between the two system falls from 1 dB to 0.9 dB, for the LS1P microphone, the difference between two heat conduction and viscous losses solution is around 1.8 dB.

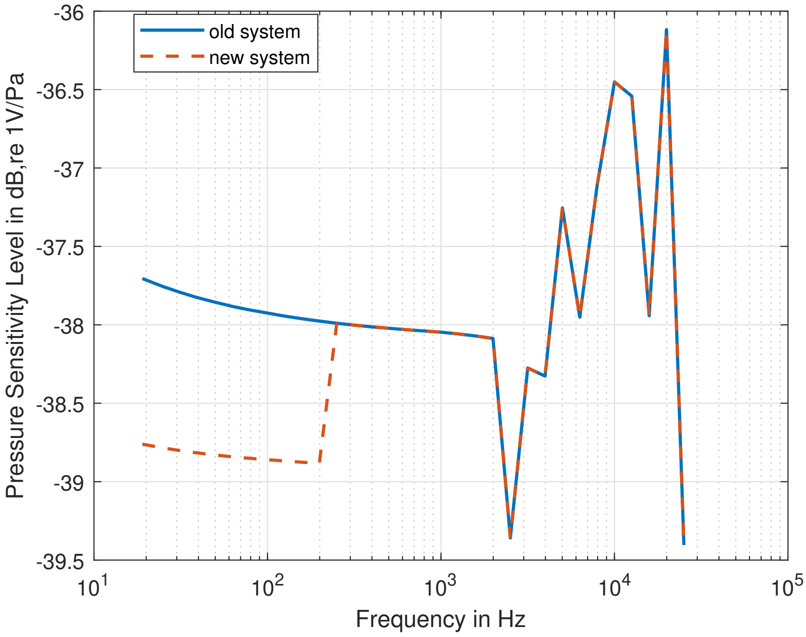



**Figure 7.1:** The pressure sensitivity level of the segmented frequency range compared with the original work for LS2P microphone

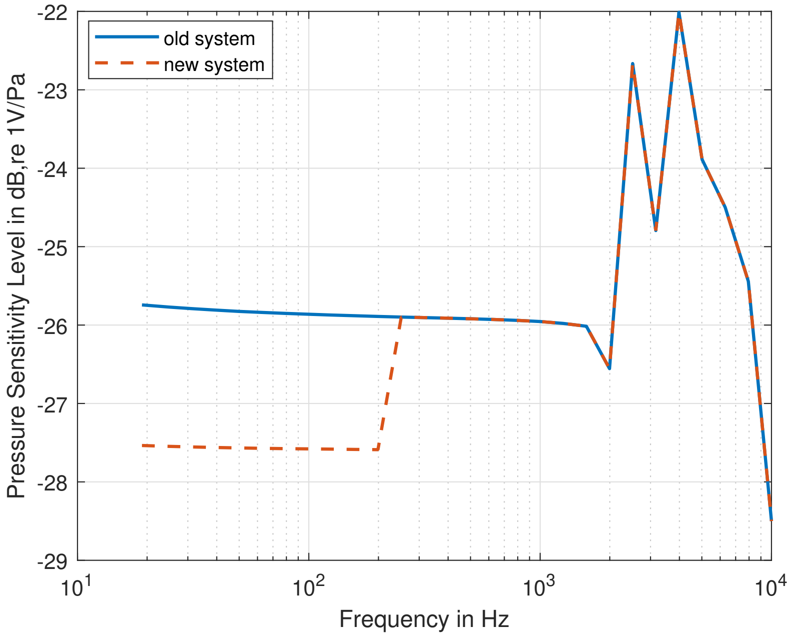



**Figure 7.2:** The pressure sensitivity level of the segmented frequency range compared with the original work for LS1P microphone

# 8
# Conclusion

This paper concentrates on investigating the variation of methods in determining microphone parameters as well as the influence of the single and combined parameters on the pressure sensitivity level. Loss factor and resonance frequency are always being measured together by the same experimental method. Each parameter has its dominant frequency range in affecting the pressure sensitivity level. Loss factor is most influential at low and high frequencies, the equivalent volume shows barely impact around resonance frequency, loss factor, and the resonance frequency the increase of front cavity depth and equivalent volume will cause the resonance frequency shift to a lower frequency, however, the loss factor and resonance frequency will move to higher frequencies. Nine standard orthogonal arrays are combined to investigate the relative influence of four parameters, for LS2P microphone, the equivalent volume is the most significant parameter in affecting the pressure sensitivity at both low and high frequency and the loss factor has almost the equal influence as the equivalent volume at high frequency. For the LS1P microphone, the front cavity depth and equivalent volume dominate the sensitivity most at low frequencies and the resonance frequency becomes the most influential at high frequency. The uncertainty of different methods is also listed and the evaluation is based on applicability, time cost, and accuracy. The uncertainty budgets chose the optimal combination of various methods. The equivalent volume is the main contribution of uncertainty for both microphone types.

There is some incompleteness of the thesis work and future work is expected to be done. As noticed the frequency range starts from 19 Hz because the calibrations at low frequencies are usually implemented by laser piston phone as a complementary method to the reciprocity calibration method. Since the limitation of the experimental trials, some incompleteness can be noticed. Only the phase plot of the LS1P microphone is demonstrated because the 1/3rd octave band data for the LS2P microphone is not detailed enough to explore the behavior around the resonance frequency. The methods comparison of loss factor and resonance frequency of LS1P microphone have only the coupler method provided. This is caused by the contradict consistency among different laboratories, further practical experiments are expected to be done in order to validate the results. Since there is a certain inconsistency among different laboratories, this causes a lack of coupler method data in the resonance frequency of the LS2P microphone. For instance In the exploring for different methods in determining the resonance frequency, the laboratory CENAM who claimed that the couplers method is used got a larger sensitivity result than laboratory NIM who used the nominal value, in this case, the data can not be used in the analysis.

# Bibliography


[1] Brüel &. Kjær, TECHNICAL REVIEW. Properties and Calibration of Laboratory, Standard Microphones Uncertainties in Microphone Frequency Responses No.1 2001.

[2] IEC 61094-2:2009, Measurement microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique, IEC (2009).

[3] Erling Sandermann Olsen and Erling Frederisksen, "Microphone acoustic impedance in reciprocity calibration of laboratory standard microphones", presented at INTER-NOISE 2013, New York(1994).

[4] Jae Gap Suh, Hack-Yoon Kim, Suzuki Yôiti, "Measurement of resonance frequency and loss factor of a microphone diaphragm using a laser vibrometer", Applied Acoustics 71 (2010) 258–261.

[5] Randall P. Wagner, Victor Nedzelnitsky, and Steven E. Fick, "New Measurement Service for Determining Pressure Sensitivity of Type LS2aP Microphones by the Reciprocity Method", Journal of Research of the National Institute of Standards and Technology, J. Res. Natl. Inst. Stand. Technol. 116, 761-769 (2011).

[6] Kleiner, Mendel, Electroacoustics, CRC Press LLC, 2013.

[7] Victor Nedzelnitsky and Randall P. Wagner, "Non-Contact Methods for Measuring Front Cavity Depths of Laboratory Standard Microphones Using a Depth-Measuring Microscope", J. Res. Natl. Inst. Stand. Technol. 113, 97-119 (2008)].

[8] N. Garg and S. Maji, "Analysis of the Effect of Microphone Parameters in Reciprocity Calibrations Using Taguchi Method", MAPAN-Journal of Metrology Society of India (September 2015) 30(3):179–190

[9] George S.K. Wong and Tony F.W. Embleton, "AIP Handbook of Condenser Microphones: Theory, Calibration and Measurements", American Institute of Physics;1995.

[10] HE Long-biao, XU Huan, NIU Feng, "Study on the Measurement of the Front Cavity Volume of the Laboratory Standard Microphone", ACTA METROLOGICA SINICA.Vol.3,No 2,March,2010.

[11] Jae Gap Suh, Hack-Yoon Kim, Suzuki Yôiti,"Measurement of resonance frequency and loss factor of a microphone diaphragm using a laser vibrometer", Applied Acoustics 71 (2010) 258–261.

[12] Vicente Cutanda Henríquez, Knud Rasmussen, Final report on CCAUV.A-K3 KEY COMPARISON.

[13] JANINE AVISON, PETER HARRIS and STEPHEN ROBINSON, FINAL REPORT: KEY COMPARISON EURAMET.AUV.A-K5, NPL Management Ltd, 2018 ISSN: 1754-2936.
[14] E. Frederiksen, "Acoustic metrology – an overview of calibration methods and their uncertainties", Int. J. Metrol. Qual. Eng. 4, 97–107 (2013).
[15] M Enge and C Hof," Emerging alternative to the well-known LS2P microphones", IOP Conf. Series: Journal of Physics: Conf. Series 1065 (2018) 222010.
[16] IEC61094-1:2000, Measurement microphones – Part 1: Specifications for laboratory standard microphones.