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Study of an active-reactive absorber

Master Thesis

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ABSTRAKT

Tato práce je o možnostech zatlumení akustické energie vyzařované vlnovodem pomocí pasivního reaktivního absorberu a aktivního absorberu. V první části je úvod do teorie akustických vlnovodů a odvození rovnic potřebných pro výpočet výstupní akustické impedance válcového vlnovodu z dvou akustických tlaků. Další část se zabývá návrhem experimentálního systému a systému pro měření vstupní a výstupní akustické impedance a útlumu testovaných konfigurací. Následují výsledky měření a jejich vyhodnocení.

ABSTRACT

This work is about possibilities of attenuation of acoustical energy radiated by a waveguide with passive reactive absorber or active absorber. In the first part is the introduction to theory of acoustic waveguides and derivation of equations, that are necessary for estimation of the output acoustic impedance of the waveguide from two acoustic pressures. The following part is about designing of the experimental system and system for measuring of the input and output acoustic impedance and insertion losses of tested configurations. At the end, measurements and their evaluation are presented.

KLÍČOVÁ SLOVA

Pasivní reaktivní absorber, aktivní absorber, vstupní akustická impednace vlnovodu, výstupní akustická impedance vlnovodu, vložný útlum

KEY WORDS

Passive reactive absorber, active absorber, input acoustical impedance of the waveguide, output acoustical impedance of the waveguide, insertion losses

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V Praze dne ....

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List of Abbreviations and Symbols

A – 1. position of microphone for measuring acoustic impedance

B – 2. position of microphone for measuring acoustic impedance

ABEC – software for simulating acoustic structures (BEM)

ACS – active control system

AkAbak – software for simulating acoustic structures (analyticaly)

c_o – speed of sound in the air

C_p – specific heat capacity

D – inside tube waveguide diameter

DSP – digital signal processor

dx – distance between microphones for measuring output acoustic impedance

H – relatively calibrated ratio - H_{mes} / H_{cal}

H_{2B1A} – ratio of pressures on microphones in configuration 2B1A

H_{2A1B} - ratio of pressures on microphones in configuration 2A1B

H_{cal} – calibrating matrix

H_{mes} – ratio of pressures on microphones in configuration 2B1A

k – wave number

L – tube waveguide length

Matlab – program for mathematical modeling

p – acoustic pressure

p_{in} – acoustic pressure in the beginning of the waveguide

p_{out} - acoustic pressure in the end of the waveguide

P_v – viscose losses

PVC - polyvinilchlorid

P_t – thermal losses

p_{xo} - acoustic pressure in the point xo

p_{x1} - acoustic pressure in the point x1

p_{x2} - acoustic pressure in the point x2

r – inside radius of tube waveguide

R_2 – coefficient for analytical modeling of open tube waveguide termination

R_{x2} – reflection coefficient in point x2 t – temperature in K

T-S – Thielle - Small

u – specific volume velocity

U– volume flow velocity

U_{1A} – voltage on the microphone 1 at position A

U_{1B} – voltage on the microphone 1 at position B

U_{2A} – voltage on the microphone 2 at position A

U_{2B} – voltage on the microphone 2 at position B

v_{in} -flow velocity in the beginning of the waveguide

v_{out} -flow velocity in the end of the waveguide

v_{xo} -acoustic pressure in the point x_o

x_o – point between the microphones for measuring output acoustic impedance

X1 – distance in which microphone 1 is mounted (measured from tube waveguide beginning)

X2 -distance in which microphone 2 is mounted (measured from tube waveguide beginning)

Y_c – acoustic admittance

Y_t – acoustic admittance caused by thermal losses

z – specific acoustic impedance

Z- acoustic impedance

Z_o – specific acoustic impedance in the beginning of the waveguide

Z_c – specific acoustic impedance in the beginning of the waveguide

Z_{in} -– specific acoustic impedance in the beginning of the waveguide

Z_{out} -– specific acoustic impedance in the end of the waveguide

Z_{out1} -– specific acoustic impedance in the end of the waveguide with closed end

Z_{out2} -– specific acoustic impedance in the end of the waveguide with open end

Z_v -– specific acoustic impedance in the beginning of the waveguide

Γ – complex wavenumber with losses

δ_2 – coefficient for end correction estimation

ρ_o – air density

1 Introduction

Dimensions and forms of acoustic waveguides define from the most part their acoustic parameters, hence their acoustic properties. These properties do not always meet our requirements. The goal of this thesis is to find a configuration of a waveguide that optimizes the attenuating system.

1.1 Reducing Radiated Acoustic Pressure of Waveguides

With no respect to specific installation, we usually need to attenuate some undesirable frequencies. There are several ways to attenuate sound radiated by the waveguide. The problem of most of them is that they are affecting the input acoustic impedance of the waveguide. What we want to achieve is to attenuate noise or sound with no effect on the input acoustic impedance. Acoustic impedance of the waveguide is frequency dependent and its changes are also frequency dependant. In the optimal case, our attenuating system should not affect the input acoustic impedance at any frequency. This is impossible to realize, so we will try to minimize the effect of attenuating system on the input acoustic impedance in the part of the spectrum according to a specific application. Some solutions are effective at low frequencies, some are effective at high frequencies, but it is always a compromise between the influence of the attenuating system on the input acoustic impedance and how much the system attenuates sound or noise and its usable frequency bandwidth.

1.2 Application on Musical Instruments

This work is part of the project "Transducers pour la facture instrumentale", which started at Université du Maine in 2011. The aim of this project is to find ways to decrease radiated sound energy of musical instruments, increase their frequency bandwidth and modify their sound character. In case of this work the aim is to pursue experimental study on passive reactive absorbers and active absorbers, which are based on modification of the output acoustic impedance of wind instrument (for example trumpet) waveguide.

2 Theory of Acoustic Waveguides

The acoustic waveguide is a structure, which guides sound waves. Geometry of the waveguide strongly affects its properties. For comparison, a waveguide behaves like a transformer in electric circuits, where transformation ratio between primary (input) and secondary (output) part (in idealized case estimated as ratio of turns on the input and output N1/N2) is eqvivalent to the ratio of input and output voltage. In acoustics the ratio of the input and output surfaces of the waveguide element is equivalent to the ratio of acoustic pressures on the input and output of such element.

2.1 Radiated Acoustic Power

Because of the directivity of any waveguide, we cannot calculate total radiated acoustic power from acoustic pressure measured at one point [9]. If the waveguide is circularly symmetrical, we have to measure a directivity pattern in one plane, where the axis of symmetry is part of it. We have to do this measurement in perfectly anechoic chamber. Another way to find radiated acoustic power is to compute it from the acoustic pressure and the flow velocity measured at the end of the waveguide [7]. The acoustical impedance is their ratio and it is directly related to the amount of energy, which is radiated by particular waveguide [33].

2.1.1 Relation between Acoustic Output Impedance and Radiated Power Pa = Re(Za).v^2, with v being the Volume Flow Velocity

As in electrical circuits the power equals to the current multiplied by the voltage, in acoustics the acoustic power equals to the acoustic pressure multiplied by the volume flow velocity. In the same way the electrical power is defined as real part of the electrical impedance multiplied by the square of voltage and the acoustic power is defined as real part of the acoustic impedance multiplied by the square of the volume flow velocity [33]. To reduce radiated acoustic power we have to reduce real part of the waveguide output acoustic impedance, or reduce the volume flow velocity. Both conditions lead to the requirement to absorbe as much energy as possible.

2.1.2 Ways to Reduce Acoustic Power

We have two ways to do that. We can use a passive or active attenuator. First option is based on using some absorption material or an object, which changes the waveguide acoustic impedance. This solution will not attenuate only required narrow frequency band and also it is not possible to control its properties over the time. Another problem of this solution in most applications is, that the absorption material will affect airflow in the waveguide and change its input acoustic impedance. Second option is based on using the active control system (ACS) [25]. It works on the principle of observing acoustic field inside or/and outside the waveguide and through a specific feedback controller and actuator it affects conditions in the waveguide. It could be used for example in the ventilation conduits, tunnels, vented tubes, or wind musical instruments. With ACS we can do the following two things:

- Attenuating
- Spectrum shaping

To get optimal results we have to be able attenuate all frequencies we want to work with as much as possible [3]. To achieve that, we need an acoustic system with very specific properties.

2.1.2.1 Rigid Attenuator

Passive attenuators have one huge advantage – they do not need any source of energy. They work on principle of converting acoustic energy into thermal energy. They are usually cheap and easy to build. Their biggest disadvantage is that for low frequencies they have to be really big to work correctly. In waveguide systems they are also usually shifting resonances of the input impedance and affecting the airflow. Either, we cannot easily change its properties. Rigid attenuators are usually used in musical instruments. They do not have any damping parts. Principle of their function is that they completely change characteristics of the waveguide, in which they are installed. We can divide them into two groups. The first group have a hole inside them and the second has a hole around them, when they are installed. Their biggest advantage is that they are very effectively reducing acoustic level produced by the musical instrument. They have very variable impact on the musical instrument spectrum [19], but most of them are more efficient at high frequencies. Their huge disadvantage is that they are strongly affecting the airflow and the input acoustical impedance of the waveguide. Because of that influence on the airflow, they are not used in other applications like ventilation systems. Influence of simple rigid mute on the input and output acoustical impedance of the waveguide will be investigated later in this thesis.

2.1.2.2 Passive Reactive Absorber

This is not a very common solution. It works on principle of modifying acoustical impedance at the end of the waveguide. At the end of the waveguide, there is small speaker (its cone directed into the waveguide) and at the electric port of this speaker there is an electric load connected. It should have similar effect on the waveguide output spectrum as the rigid mute, but the difference is, that it should have much smaller impact on the waveguide input acoustic impedance [27]. As all passive attenuators, even this one negatively affects airflow in the waveguide. This kind of passive attenuating system will also be investigated in this thesis later.

2.1.2.3 Active Absorber

The ACS works on principle of observing acoustic field inside or/and outside the trumpet and through specific feedback controller and actuator it affects an acoustic field. The simplest case is shown in diagram in Figure 1. It is important to choose and optimize the position of error microphone and actuator, choose microphone and actuator with most suitable parameters and design the controller. The controller can be analogue or digital. According to previous research the digital one should be much more suitable for this application [3]. Except maximizing of measurable performance we also have to consider system ergonomics, usability and price. In general ACS usually works well only at low frequencies [25, 3].

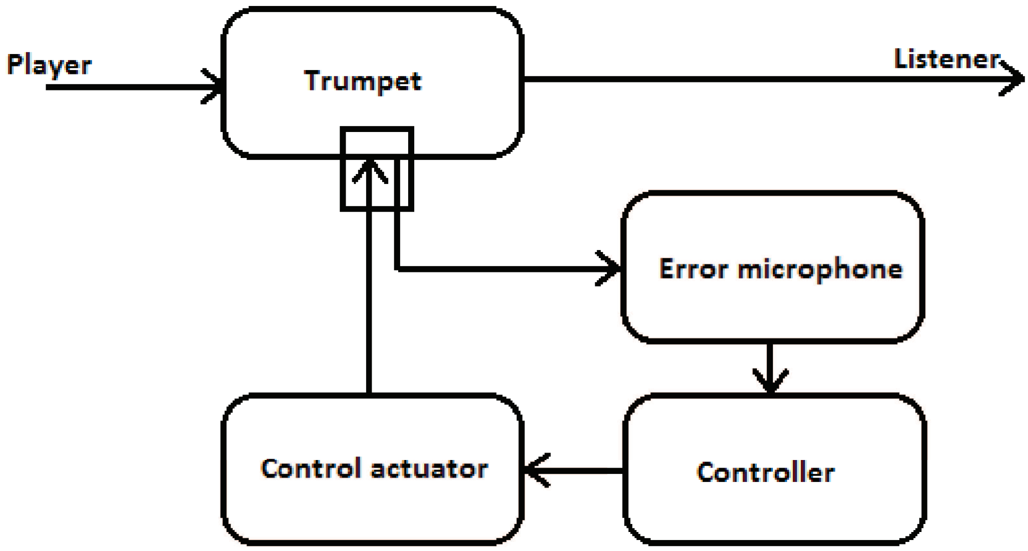


Figure 1. Active control system block diagram

2.2 Acoustical Impedance

Acoustic impedance is the ratio of acoustic pressure *p* to acoustic volume flow *U*. So we define z *=p/U*. *z* usually varies strongly when you change the frequency. The acoustic impedance at a particular frequency indicates how much sound pressure is generated by a given air vibration at that frequency.[12] "The specific acoustic impedance *Z* is the ratio of acoustic pressure to specific flow, which is the same as flow per unit area, or flow velocity *v*. In all cases, 'acoustic' refers to the oscillating component. With this proviso, we can say that acoustic impedance z = *pressure/flow* and specific acoustic impedance Z = *pressure/velocity*." [12] By the input acoustic impedance the specific (also known as normalized) acoustic impedance at the beginning of the tube waveguide is meant. It is an acoustic load, which the wave "sees" when it gets to the point, where this input acoustic impedance is defined. It is a complex value, the higher its module is, the easier the wave at that frequency can pass the place, where the impedance is defined. By the output acoustic impedance the specific acoustic impedance in the end of the tube waveguide is meant [33].

2.2.1 Output Acoustical Impedance (Real and Imaginary Part, Open and Closed End)

The output acoustic impedance is directly related to the radiated power. It has real and imaginary parts. The real part equals to the acoustic resistance the imaginary to the acoustic reactance. Resistance is caused by friction and the energy losses caused by the sound radiation of an acoustic system and reactance is caused by acoustic mass and elasticity. The real part should be low (for reducing radiated power) and the imaginary part should be in the best case the same as in the configuration with anything in front of the waveguide. For the closed tube termination Z_{out} equals to zero at all frequencies (2.2.1.01). Output acoustic impedance of open tube end termination is defined by (2.2.1.02) [33].

$$Z_{out1}=0 \qquad 2.2.1.01$$

$$Z_{out2}=\frac{j}{\pi\cdot r^2\cdot\tan\left(k\cdot\delta_2+\frac{1}{2\cdot j\cdot\log R_2}\right)} \qquad 2.2.1.02$$

$$R_2 = \frac{\left(1+0.2\cdot k\cdot r-0.084\cdot(k\cdot r)^2\right)}{\left(1+0.2\cdot k\cdot r+\left(\frac{1}{2-0.084}\right)\cdot(k\cdot r)^2\right)} \quad 2.2.1.03$$

$$\delta_2 = \frac{0.6133\cdot\left(1+(0.044\cdot k\cdot r)^2\right)}{\left(1+(0.19\cdot k\cdot r)^2\right)\cdot r} \quad 2.2.1.04$$

2.2.2 Role of the Input Acoustical Impedance for Wind Instruments

The input acoustic impedance of the wind instruments is very important, because its resonant frequencies are directly related with resonant frequencies of the particular musical instruments. If these frequencies are shifted, it is very difficult for the player to play in tune. That is the reason why attenuating system should not affect these resonant frequencies too much [3].

2.3 Acoustical Impedance Measurement Techniques

For measuring acoustic impedance at some point, we have to know the flow velocity and the acoustic pressure at that point. Acoustic impedance is defined as their ratio.

2.3.1 Output Acoustical Impedance Measurement Techniques

By the output acoustic impedance we mean the acoustic impedance at the end of the straight tube waveguide. To compute the acoustic impedance at the end of the waveguide, the knowledge of flow velocity and acoustic pressure there is needed. From practical reasons were measured two acoustic pressures nearby the waveguide end. Further the flow velocity and the acoustic pressure between them were computed. Then the acoustic impedance at that point was estimated and this impedance was recomputed to the end of the waveguide [33].

2.3.1.1 Theory

For better orientation the in following chapters please see Figure 3., in which all important points and variables, that are used in the equations are marked. The output acoustic impedance at the end of the waveguide (Z_{out}) is defined as the ratio between acoustic pressure (p_{out}) at the end of the tube and flow velocity at the end of the tube (v_{out}). To compute the acoustic impedance at the end of the tube, we have to know the acoustic pressure and the flow velocity at the point in the middle between measuring microphones. Acoustic pressure at that point (p_{xo}) is defined by (2.3.1.1.02), flow velocity at that point (v_{xo}) is defined by (2.3.1.1.03). To compute the flow velocity at the end of waveguide, we have to use the transfer matrix between the acoustic pressure and the flow velocity at two points x_1 and x_2 (2.3.1.1.04). From this matrix formulas for the flow velocity at the end of the tube (v_{out}) are estimated – (2.3.1.1.05). Acoustic pressure at the end of the waveguide can be computed according to (2.3.1.1.06). Output acoustic impedance then is defined by (2.3.1.1.01). Variable k is the wavenumber and is defined by (2.3.1.1.07) [33].

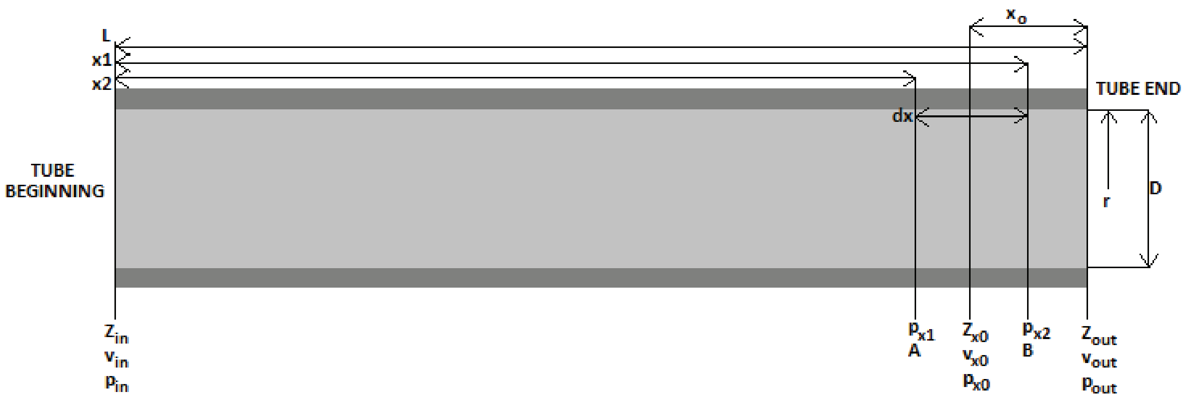


Figure 3. Picture with all important points and variables, which are used in the following equations

$$Z_{out} = \frac{p_{out}}{v_{out}} \qquad 2.3.1.1.01$$

$$p_{x0}=\frac{p_{x1}+p_{x2}}{2\cdot\cos(k\cdot dx)}$$ 2.3.1.1.02

$$v_{x0}=\frac{p_{x1}-p_{x2}}{2\cdot j\cdot\rho_0\cdot c_0\cdot\sin(k\cdot dx)}$$ 2.3.1.1.03

$$\begin{pmatrix}p_{x1}\\ v_{x1}\end{pmatrix}=\begin{pmatrix}\cos(k\cdot(x_2-x_1)) & j\cdot c_0\cdot\rho_0\cdot\sin(k\cdot(x_2-x_1))\\ j\cdot\frac{1}{c_0\cdot\rho_0}\cdot\sin(k\cdot(x_2-x_1)) & \cos(k\cdot(x_2-x_1))\end{pmatrix}\cdot\begin{pmatrix}p_{x2}\\ v_{x2}\end{pmatrix}$$ 2.3.1.1.04

$$v_{out}=-j\cdot\frac{p_{x0}}{c_0\cdot\rho_0}\cdot\sin(k\cdot x_0)+v_{x0}\cdot\cos(k\cdot x_0)$$ 2.3.1.1.05

$$p_{out}=j\cdot v_{x0}\cdot c_0\cdot\rho_0\cdot\sin(k\cdot x_0)-p_{x0}\cdot\cos(k\cdot x_0)$$ 2.3.1.1.06

$$k=\frac{2\cdot pi\cdot f}{c_o}$$ 2.3.1.1.07

Unfortunately, the results given by this method proved to be inaccurate. To get better results, the fact that Z_c is not constant needed to be incorporated. New equations are defined by the following formulas.

$$Z_c=\sqrt{\frac{Z_v}{Y_t}}$$ 2.3.1.1.08

$$Z_v=k\cdot\rho_o\cdot c_o\cdot(P_v\cdot j(1+P_v))$$ 2.3.1.1.09

$$Y_t=\frac{k}{\rho_o\cdot c_o}\cdot(P_t+j(P_t+1))$$ 2.3.1.1.010

$$P_v=\frac{\sqrt{\frac{l_v}{k}}}{r}\quad r=radius\ of\ the\ tube\ waveguide$$ 2.3.1.1.011

$$P_t=(\gamma-1)\cdot\frac{\sqrt{\frac{l_t}{k}}}{r}\quad\gamma=1.4$$ 2.3.1.1.012

$$\mu=1.708e^{-5}\cdot(1+0.0029\cdot t)$$ 2.3.1.1.013

$$\rho_o \cdot c_o = \frac{1.2929 \cdot 331.45}{\sqrt{273.16 \cdot (273.16 + t)}} \qquad 2.3.1.1.014$$

$$l_v = \frac{\mu}{\rho_o \cdot c_o} \qquad 2.3.1.1.015$$

$$l_t = \frac{\lambda}{\rho_o \cdot c_o \cdot C_p} \quad \lambda = 0.0024\, W\, m^{-1} K^{-1} \quad C_p = 1.01210^3\, J\, kg^{-1} K^{-1} \qquad 2.3.1.1.016$$

Equations for computing p_{xo} and v_{xo} are the same, but transformation matrix change into (2.3.1.1.019). Acoustic pressure and velocity, which are defined by p_{out} and v_{out} are then defined by (2.3.1.1.022) and (2.3.1.1.023). For recomputing acoustic impedance from the point indexed x_o to the point indexed x_{out}, we can use equation (2.3.1.1.024) [33].

$$p_{x0} = \frac{p_{x1} + p_{x2}}{2 \cdot \cosh(\Gamma \cdot dx)} \qquad 2.3.1.1.017$$

$$v_{x0} = \frac{p_{x1} - p_{x2}}{2 \cdot Z_c \cdot \sinh(\Gamma \cdot dx)} \qquad 2.3.1.1.018$$

$$\begin{pmatrix} p_{x1} \\ v_{x1} \end{pmatrix} = \begin{pmatrix} \cosh(\Gamma \cdot (x_2 - x_1)) & Z_c \cdot \sinh(\Gamma \cdot (x_2 - x_1)) \\ Y_c \cdot \sinh(\Gamma \cdot (x_2 - x_1)) & \cosh(\Gamma \cdot (x_2 - x_1)) \end{pmatrix} \cdot \begin{pmatrix} p_{x2} \\ v_{x2} \end{pmatrix} \qquad 2.3.1.1.019$$

$$\Gamma = \sqrt{Z_v \cdot Y_t} \qquad 2.3.1.1.020$$

$$Y_c = 1 / Z_c \qquad 2.3.1.1.021$$

$$p_{out} = -p_{xo} \cdot \cosh(\Gamma \cdot x_0) + v_{xo} \cdot Z_c \cdot \sinh(\Gamma \cdot x_0) \qquad 2.3.1.1.022$$

$$v_{out} = -p_{xo} \cdot Y_c \cdot \sinh(\Gamma \cdot x_0) + v_o \cdot \cosh(\Gamma \cdot x_0) \qquad 2.3.1.1.023$$

$$Z_{out} = Z_c \cdot \left(\frac{\left(\frac{Z_o}{Z_c}\right) - j \cdot \tanh(\Gamma \cdot x_0)}{1 - \left(\frac{j \cdot Z_o}{Z_c \cdot \tanh(\Gamma \cdot x_0)}\right)} \right) \qquad 2.3.1.1.024$$

2.3.1.2 Transfer Matrix (Verification)

For using equations derived above, it is necessary to verify them. There are two basic equations, which have to be verified. First is the transfer matrix, which was used for recomputing the acoustic pressure and the flow velocity from the point between microphones to the end of the waveguide. The second equation which was used is for computing of acoustic pressure and velocity between microphones from pressures on the microphones. In this sub-chapter transfer matrix was verified. For that the fact, that different termination of the waveguide can be simulated was used (see chapter 2.2.1). Two terminations were used – the waveguide terminated by acoustic short-circuit (1) and the radiation impedance without baffle (2). Both were derived in Chapter 2.2.1. When acoustic impedance at the end of the waveguide was known, the transfer matrix was used to compute acoustic impedance at the beginning of the waveguide and then the inverse transfer matrix was used to compute acoustic impedance at the end of the waveguide. Afterwards the output of this simulation was compared to the acoustic impedance which was used as the input of the whole simulation. Simulations for model with losses were performed. The acoustic impedance in the middle of the tube was computed from the simulated output acoustical impedance by means of the transfer matrix and then the impedance in the beginning of the tube was computed by means of application of the same transfer matrix from previously computed acoustical impedance in the middle of the tube waveguide. Next from this input acoustic impedance the acoustic impedance in the end of the tube waveguide was computed by means of the inversed transfer function. In both cases the output acoustic impedance was exactly the same as the simulated one as it was in the beginning.

2.3.1.3 Pressure and Velocity (Verification)

Similarly as the transfer matrix the equations for computing acoustic pressure and velocity from two microphones in the middle between of them were verified. Two terminations were used. The acoustic impedances between microphones and at the beginning of the waveguide were used. Then formula 2.3.1.3.01 to compute the reflection coefficient R_{x2} at the point in which is second microphone was used and then equations for computing acoustic pressures p_{x1} and p_{x2} at points, at which the microphones are were used. Variable x_1 determined the distance of the first microphone from the beginning of the waveguide, x_2 determined the distance of the second microphone from the beginning of the waveguide. From the acoustic impedance at the end of the waveguide Z_{in} was computed. The transfer matrix with losses was used. From p_{x1} and p_{x2} acoustic impedances in the middle of the microphones were computed. Equation 2.3.1.1.024 which involves losses was used. Finally, the acoustic impedances were estimated from the acoustic impedances which were computed directly from the transfer matrix (with losses) from the acoustic impedance in the end of the waveguide. This model worked with normalized impedance [33].

$$R_{x2}=\frac{(Z_{x2}-1)}{(Z_{x2}+1)} \qquad 2.3.1.3.01$$

$$p_{x1}=e^{(\Gamma\cdot(x_2-x_1))}+R_{x2}\cdot e^{(-\Gamma\cdot(x_2-x_1))} \qquad 2.3.1.3.02$$

$$p_{x2}=1+R_{x2} \qquad 2.3.1.3.03$$

2.3.1.4 Microphones Calibration

To obtain accurate results it is important to have calibrated microphones. They do not have to be calibrated in absolute sensitivity and they do not have to be calibrated in spectral domain either. But they have to be relatively calibrated very precisely. Absolute values of their acoustic pressures are not important, but their ratio is. The relative calibration which was used is described briefly below. Transfer function of the microphone 1 at position A (U_{1A}) and transfer function of the microphone 2 at position B (U_{2B}) were measured. Their ratio is $H_{2B1A} = U_{2B}/U_{1A}$. Then microphones were switched and transfer function of microphone 2 at position A (U_{2A}) and transfer function of microphone 1 at position B (U_{1B}) were measured. Their ratio is $H_{2A1B} = U_{2A}/U_{1B}$. Transfer function of the calibrating file H_{cal} is than defined by 2.3.1.4.01. When microphone 1 was given back to position A and microphone 2 was given back to position B and acoustic pressures U_{1A} and U_{2B} on them were measured, their relatively calibration ratio H from equation 2.3.1.4.02, where $H_{mes} = U_{2B}/U_{1A}$, could be estimated [33].

$$H_{cal} = \sqrt{H_{2B1A} \cdot H_{2A1B}} \qquad 2.3.1.4.01$$

$$H = \frac{H_{mes}}{H_{cal}} \qquad 2.3.1.4.02$$

2.4 Insertion Losses

Insertion losses are defined as the difference in the acoustic pressure at a defined point between the configuration without any object in front of the waveguide and the configuration with some object in front of the waveguide. The higher these insertion losses are, the bigger influence on attenuation in defined point the tested object have.

2.5 BEM

ABEC is program for simulating acoustic structures. It uses the Boundary elements analysis. Its disadvantage is, that simulation has huge requirements for computing power and even on fast modern computer the processing is very time consuming. The acoustic impedance at the beginning of the waveguide was simulated. Due to the fact that ABEC does not take into consideration losses inside the structure the simulation of real part of the output acoustic impedance is very inaccurate and that is the reason why it was not shown for all configurations in this thesis. To find the resonances in the input acoustic impedance this is not a problem. All we have to do is to realize, that quality factor of those resonances will be in reality much lower. The same is also true for the quality factor of peaks in the acoustic pressure.

3 Experimental System

This section presents an experimental system on which influence of the waveguide termination by rigid disc, passive reactive absorber and active absorber on the input acoustical impedance, the output acoustical impedance and the insertion losses were studied. For the sake of experiments a prototype was designed, which is applicable in all studied configurations.

3.1 System under Study

In this phase of research it is not necessary to use a system with the same properties as for example a musician trumpet has. More important is to find out how attenuating configurations behave. Because of that much simplified model of the waveguide was chosen. It has a shape of a straight tube. Also its diameter and length were adapted to be easy to build. The input and output acoustic impedance had to be measured. It was considered more practical to divide the experiment into two separate experiments. The first is for measuring the input acoustic impedance and the second for measuring of the output acoustical impedance. In both experiments waveguides and attenuating systems of the same properties and geometric configurations were used. The reason why it was decided to do that is, it would be very time inefficient to remounting waveguide from the input acoustic impedance sensor to system for measuring output acoustic impedance and vice versa each time we wanted to measure the other. The system under study is a cylindrical tube with the length 200 mm and inner diameter 33 mm. The outside diameter is 40 mm. This tube is excited either by the impedance sensor [14, 15] or by a loudspeaker mounted in a closed box. Different terminations are placed in front of the tube for studying their effect on the input impedance, radiation impedance and the radiated pressure on axis.

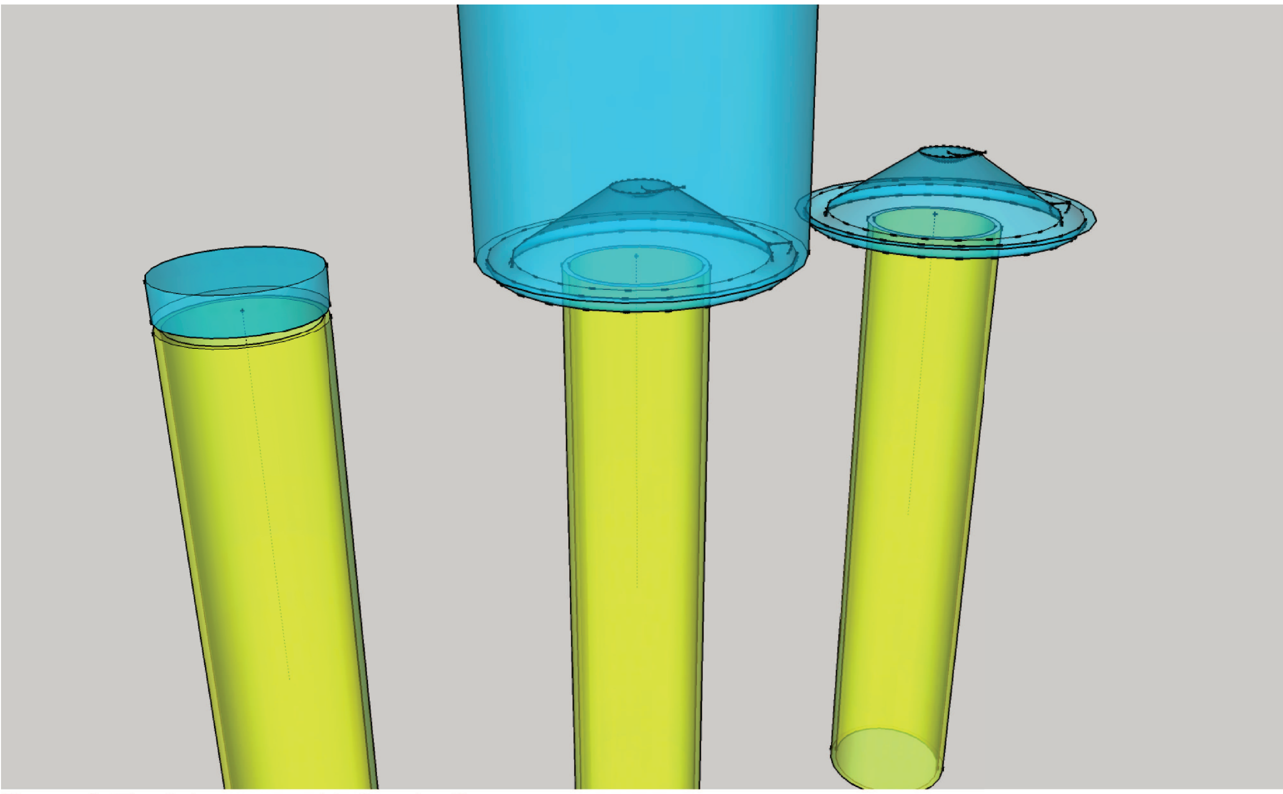


Figure 4. The tube waveguide terminations

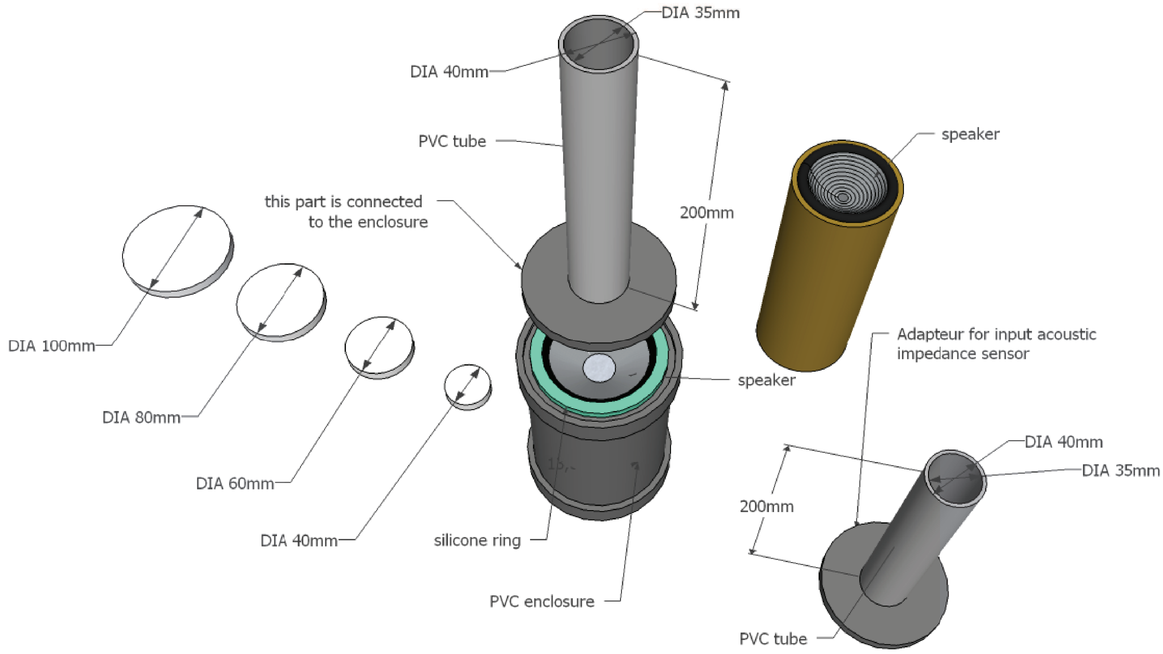


Figure 5. Parts of experimental system

3.1.1 Rigid Attenuator

Configurations which were studied in this part of work are composed of the cylindrical waveguide and the rigid disc, which is placed close to the end of the waveguide. Influence of diameter of the rigid disc and influence of its distance from the end of the waveguide on the input and output acoustic impedance of the waveguide were studied. Then this input and output acoustic impedance were compared with the input and output acoustic impedance of the waveguide without any rigid disc in front of it. Measurements of these configurations were also compared with analytical model which was made in MATLAB (configuration without rigid disc only) and simulations in ABEC. During measurements a lot of configurations were tried and it was decided to present in this thesis the following four configurations, on which influence of distance between the end of the waveguide and rigid disc and influence of rigid disc diameter were described:

Below are presented four experimental configurations used in the study:

1. Configuration without attenuator
2. Configuration with 40 mm rigid circular attenuator 2 mm from waveguide
3. Configuration with 40 mm rigid circular attenuator 5 mm from waveguide
4. Configuration with 100 mm rigid circular attenuator 5 mm from waveguide

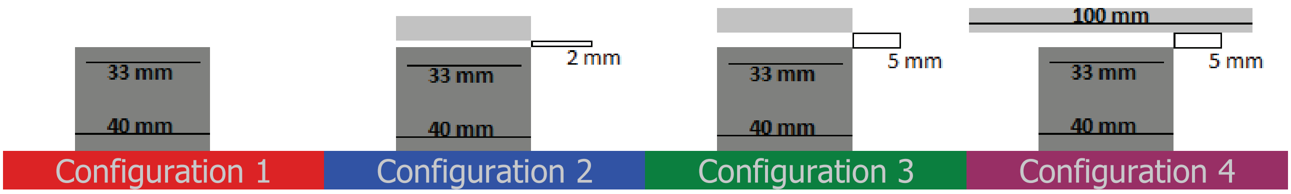


Figure 6. Tested configurations - rigid disc attenuator, the waveguide length was 200 mm

3.1.2 Passive Reactive Absorber

Configurations which were studied in this part of work are composed of tube waveguide and speaker, which was placed in front of the tube waveguide in distance of few millimeters. The speaker could have its own closed enclosure. On the connector of the speaker an electrical load with which would system composed of the speaker (with enclosure) and this electrical load will get into resonance on resonant frequencies of the tube waveguide should be connected. For experiments four configurations were chosen and the same speaker was used in them (two pieces of same model of speaker). It was a no-name speaker with outer frame diameter approximately 90 mm. Its T-S parameters were measured below. Two experiments were done with the speaker in enclosure and two were done with speaker without it. For experiments one distance between the end of the waveguide and speaker was chosen. It was such distance in which the basket frame of the speaker was in same plane as the end of the tube waveguide. To obtain all possible electrical loads, shorted and open contacts (infinite resistance) were used as electrical load. Those four configurations were compared with the tube waveguide without anything in front of it. All four tested configurations and configuration without anything in front of it are shown at Figure 7.

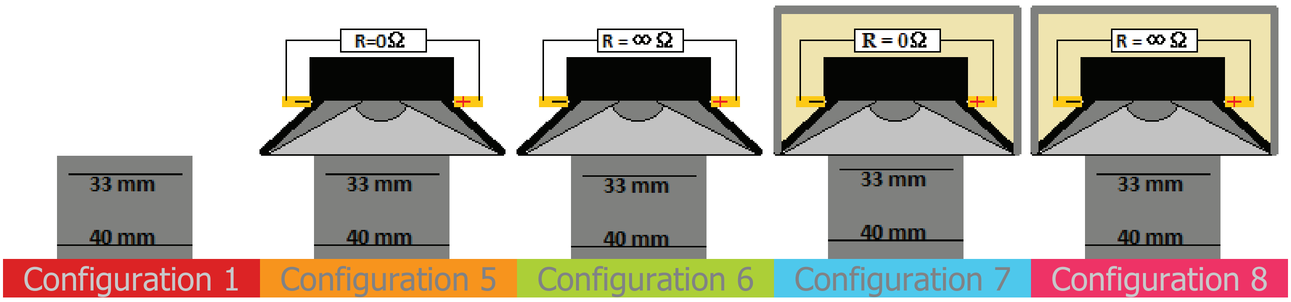


Figure 7. Tested configurations - passive active absorber, the waveguide length was 200 mm

For better understanding of the influence of speaker in front of the end of the waveguide and for simulations it is necessary to know also the parameters of the used speaker. To obtain as accurate results as possible the system CLIO was used for their measurement. In table below you can find set of measured Thiele-Small parameters. Both drivers which were used were measured.

Parameter	Re [Ω]	Fs [Hz]	Mms [g]	Rms [kg.s^{-1}]	Cms [mm.N^{-1}]	Bl [N.A^{-1}]	Vas [l]	Qms	Qes
Speaker 1	7.47	147.4	2.038	0.453	0.572	3.103	0.787	4.167	1.463
Speaker 2	7.33	138.2	2.100	0.457	0.631	3.147	0.868	3.991	1.350

Tab 1. Thiele-Small parameters of used drivers

3.1.3 Active Absorber

Configurations which were studied in this part of work were composed of the cylindrical waveguide and speaker, which was placed in front of the cylindrical waveguide in distance of few millimeters. The speaker with and without closed enclosure were tested. At the end of the tube waveguide a microphone was mounted. The signal from this microphone was amplified by preamplifier and then by amplifier. To the connectors of the speaker the amplifier was connected. It is important, that this amplified signal was shifted in phase by 180 degrees. For experiments two configurations were chosen and in both cases the same speaker (two pieces of same model of speaker) was used. It was a no-name speaker with the outer frame diameter approximately 90 mm. Its T-S parameters were measured in sub-chapter 3.1.2. One experiment was with speaker in enclosure and the second was with speaker without it. For experiments one distance between the end of the waveguide and speaker was chosen. It was such distance in which the basket frame of the speaker was in same plane as the end of the tube waveguide. The acoustical impedances were compared with acoustical impedances of the tube waveguide without anything in front of it. Both tested configurations and configuration without anything in front of it are shown in Figure 8. Feedback loop gain was set to the value at which the system was stable (there was a small reserve). As microphone G.R.A.S. Type 40DP (s.n. 101768) mounted on preamplifier Brüel&Kjær Type 2670 (s.n. 2358353) was used. As preamplifier remaining channel of four channel Brüel&Kjær NEXUS which was used as preamplifier for other microphones was used. As amplifier CANFORD audio Compact Power Amplifier 20-311 was used.

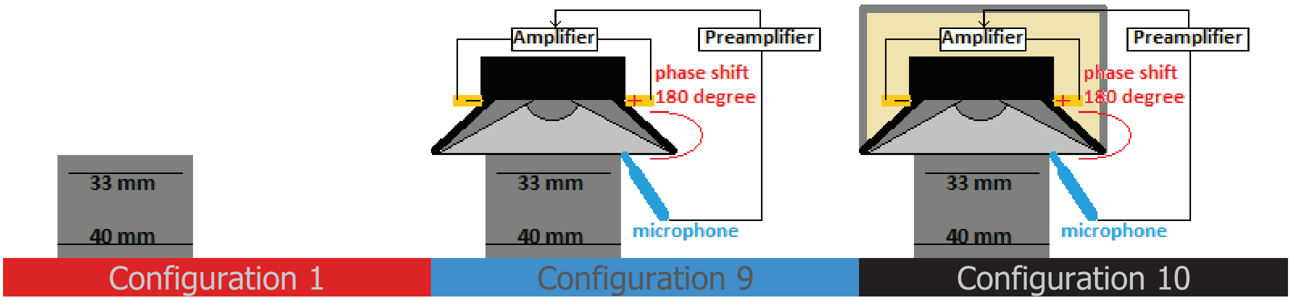


Figure 8. Tested configurations - active absorber, the waveguide length was 200 mm

3.2 Measurement System

As was mentioned above, there were two experimental systems. The first was for measuring the input acoustic impedance and the second for measuring of the output acoustic impedance. The second system was also used for measuring of insertion losses.

3.2.1 Input Acoustic Impedance

For measuring the input acoustical impedance of the waveguide a system was used, which is already constructed and available at Laboratoire d'Acoustique at Université du Maine. It is composed of two channel microphone preamplifier, power amplifier, two channels analog to digital converter with USB interface, laptop with soundcard and installed software and from input acoustic impedance sensor. On sensor the waveguide is mounted. More about this measurement system you can find in [14,15]. For the input acoustic impedance measurement sensor with one actuator and two microphones was used. For correct results the measurement system had to be calibrated first. Calibration was done by measuring the input acoustic impedance while rigid disc is mounted to the sensor instead of measured waveguide. Actuator then works in a very small volume of known properties and measuring software is able calibrate itself based on this measurement. During measuring of the input acoustic impedance the software more pursue individual measurements and then compute correlation between them. In the optimal case this correlation factor should be equal to one.

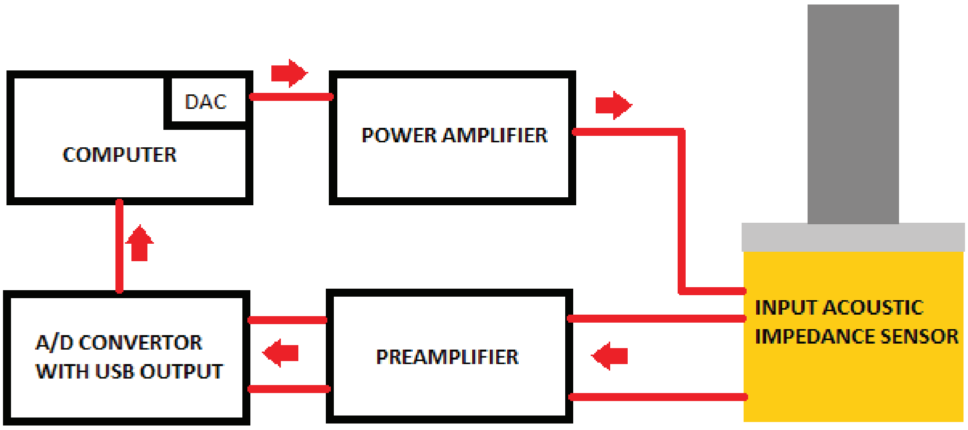


Figure 9. Block diagram - input acoustic impedance measuring system

3.2.2 Output Acoustic Impedance

By the output acoustic impedance the acoustic impedance at the end of the straight cyllindrical waveguide is meant. To compute acoustic impedance at the end of the waveguide it is necessary to know the flow velocity and the acoustic pressure there. For practical reasons two acoustic pressures nearby the waveguide end were measured. Then the flow velocity and the acoustic pressure between them were computed. Then acoustic impedance at that point was computed and afterwards this impedance was recomputed to the end of the waveguide. The microphones for measuring of the two acoustic pressures for computing the output acoustic impedance were installed close each other at the end of the waveguide. Vector from the first microphone to the second one have to be the same as direction in which the flow velocity was measured. There was also the third microphone for acoustic pressure measuring (to see insertion losses of individual configurations). Microphones for measuring flow velocity had to be calibrated very precisely. Microphones Brüel&Kjær type 4938 (s.n. 2151401 and 2611959) mounted on preampifiers G.R.A.S Type 26AC (s.n. 133469 and 151624) were used. They were relatively calibrated. Signal from them was amplified by four channel preamplifier Brüel&Kjær NEXUS (s.n. 2069429). Waveguide was excited by speaker at closed enclosure with volume 1l filled by damping material. As a signal generator Agilent 33120A controlled by a card at the personal computer was used. Signal from it was amplified by amplifier based on IO LM 3886. On its output speaker and oscilloscope LeCroy waveJet 324A for checking signal amplitude were connected. Signal generator was connected to the acquisition card at the computer for synchronization. Signal from microphone preamplifier was processed at digital to analog converter acquisition box NATIONAL INSTRUMENTS BNC-2110 which was also connected to the computer. This acquisition box was also synchronized with signal generator. Because the acquisition box was able to measure only in the time domain, the sweep sine from the signal generator was used and then results were transformed into frequency domain on computer. From these outputs in frequency domain was computed the output acoustic impedance. It is very important to check if measured signals from both microphones are in phase and if signal is not in limitation. There also should not be a gap between the microphone body and the waveguide.

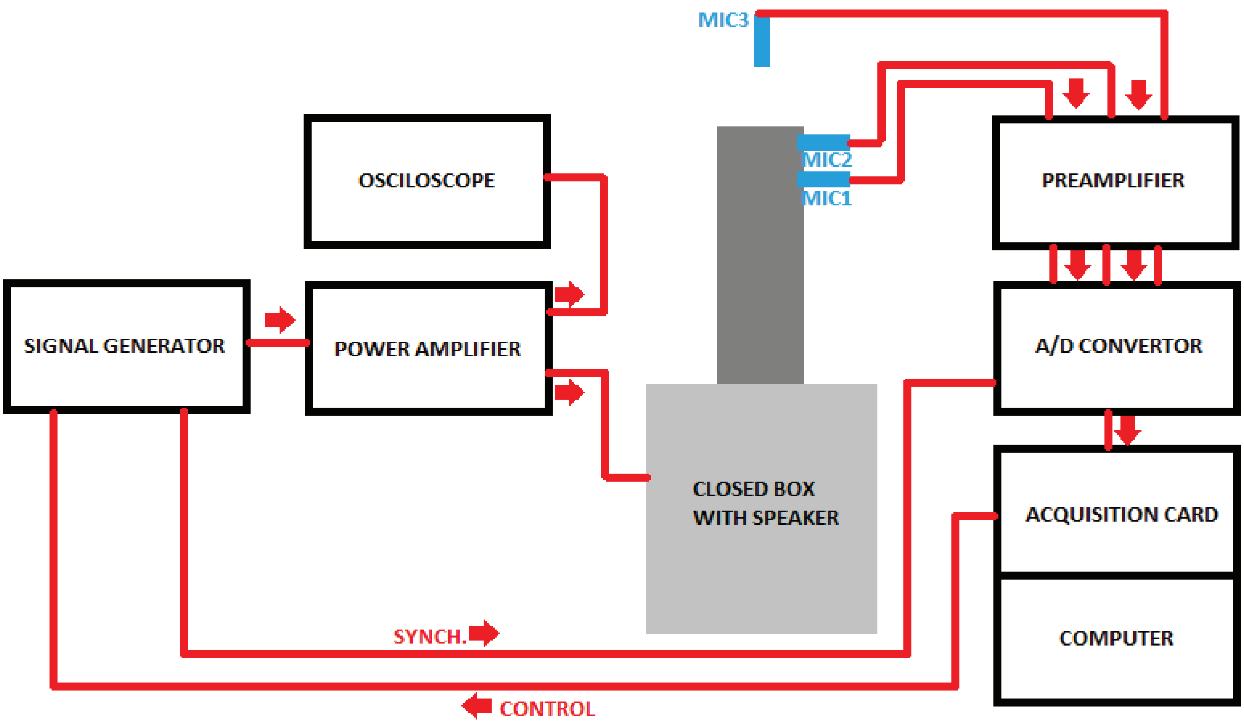


Figure 10. Block diagram - output acoustic impedance and insertion losses measuring system

3.2.3 Insertion Losses

For acoustic pressure measuring for computing insertion losses the same equipment as for measuring of acoustic pressures which were used for computing of the output acoustic impedance was used. As microphone G.R.A.S. Type 40BP (s.n. 164442) mounted on preamplifier Brüel&Kjær type 2670 (s.n. 2465440) was used. Those acoustic pressures were measured in the anechoic chamber. Insertion losses are defined as difference between acoustic pressure in defined point for case of the waveguide without anything in front of it and for case of the waveguide with an object placed in front of it.

3.3 Comparison of Measurements of the Tube with Open End with Analytical Model

For better understanding what is happening with acoustic impedance and what has influence on it and mainly for verifying results of measurements, an analytical model of the system without attenuator was made. Purely simulated characteristic, characteristic computed from the measured input acoustic impedance and the measured output acoustic impedance were compared.

3.3.1 Input Acoustic Impedance

In this sub-chapter measured acoustic impedance at the input of the waveguide, the input acoustic impedance computed from the measured output acoustic impedance and the simulated input acoustic impedance were compared. Those comparisons were done for case of open waveguide end without anything in front of it.

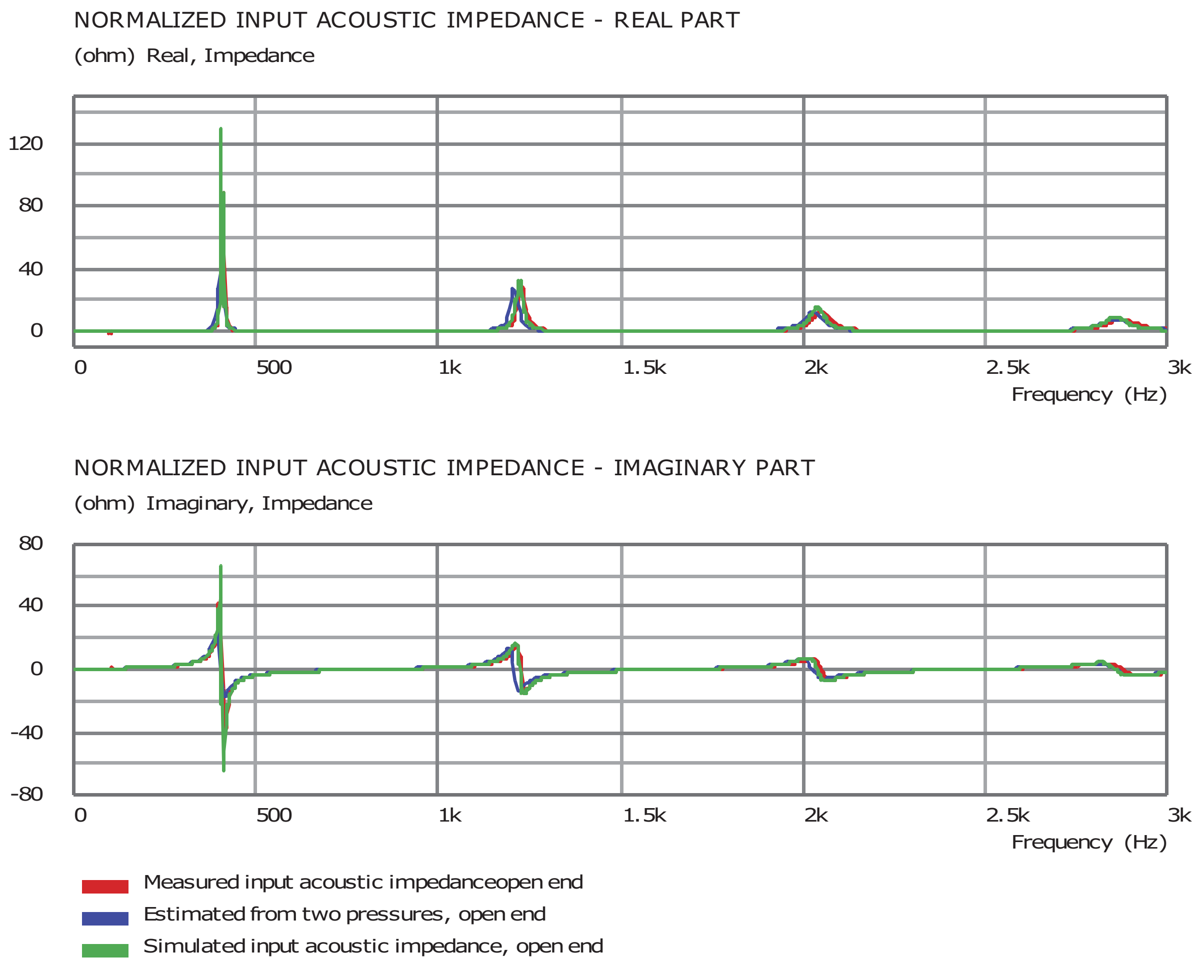
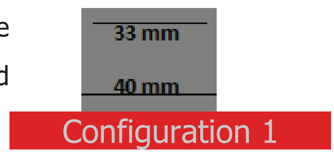


Figure 11. Open waveguide end, real part and imaginary part, comparison of the theoretical model of the input acoustic impedance, the input acoustic impedance computed from the measured acoustic impedance between two microphones and the measured input acoustic impedance.



3.3.2 Output Acoustic Impedance

In this sub-chapter the acoustic impedance at the output of the tube waveguide was compared with the output acoustic impedance computed from measured input acoustic impedance and with the theoretically modeled one. Those comparisons were done for case of open waveguide end without anything in front of it.

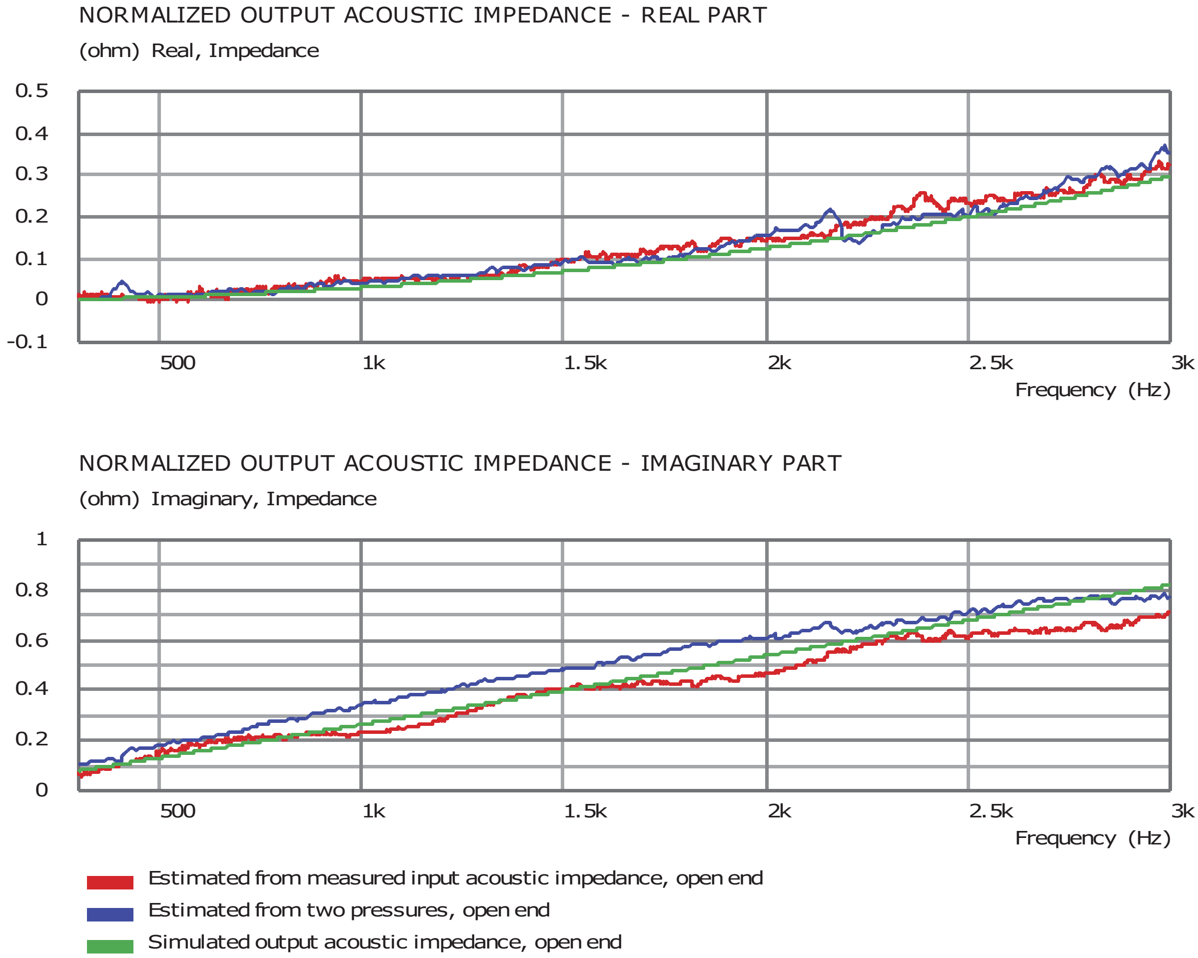
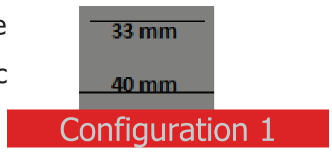


Figure 12. Open waveguide end, comparison of the theoretical model of the output acoustic impedance, the output acoustic impedance computed from the measured input acoustic impedance and the measured output acoustic impedance.



3.4 Numerical Model

ABEC is a program simulating acoustic structures. It uses Boundary elements analysis. Its disadvantage is, that simulation has huge requirements for computing power and even on fast modern computer it is very time consuming. Acoustic impedance at the beginning of the waveguide was simulated. Due to the fact, that ABEC does not take into consideration losses inside the structure the simulation of real part of the output acoustic impedance is very inaccurate and that is the reason, why output acoustic impedance is not shown in this thesis. For finding resonances at the input acoustic impedance this is not a problem. It is necessary to realize, that quality factor of those resonances will be in reality much lower. The same is also true for quality factor of peaks in the acoustic pressure.

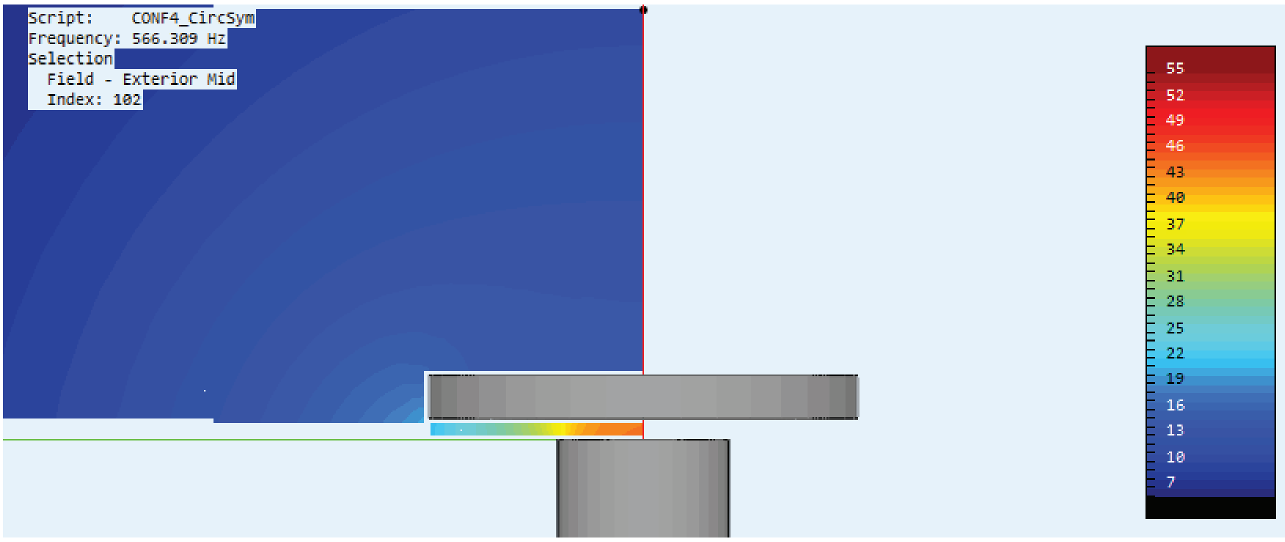


Figure 13. Example of acoustic pressure field computed around circually symetric model of configuration 4.

3.4.1 Rigid Attenuator

These simulations were performed for configurations which were presented in Chapter 3.1.1.

3.4.1.1 Input Acoustic Impedance

The input acoustic impedance of all four tested configuration simulated at ABEC and analytically estimated input acoustic impedance were compared. Due to the limitation of ABEC the quality factor of the resonances at the simulation is much higher, than they are in reality. The ABEC calculate only with losses in case of radiation into far-field.

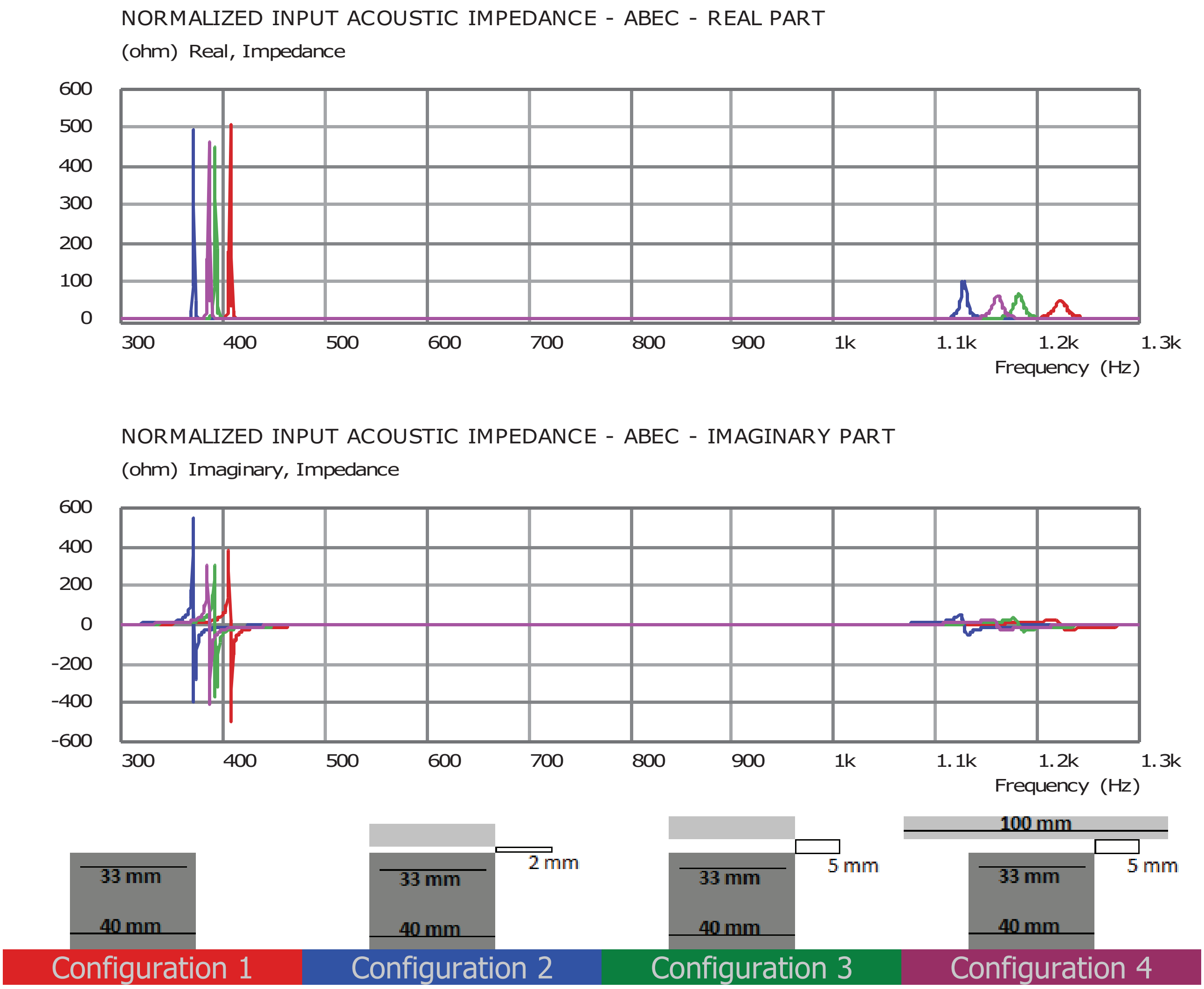


Figure 14. Simulated input acoustic impedance – real and imaginary part (different configurations are given in the sketch above). The total tube length is 20 cm.

3.4.1.2 Insertion Losses

In this sub-chapter the acoustic pressures at 1 m from the end of the waveguide for all four tested configurations were simulated. Then difference in this pressure between configuration without the rigid disc and each of other configurations was computed. Also simulations of field around the tube end of configurations with attenuator were done. Because of absence of losses in those models the peaks in frequency characteristics were very sharp. In reality the insertion losses are much lower. More interesting are directivity plots. Difference in the acoustic pressure radiated to almost any direction is small. Because of that the acoustic pressure measured at one point can represent radiated acoustic power relatively precisely.

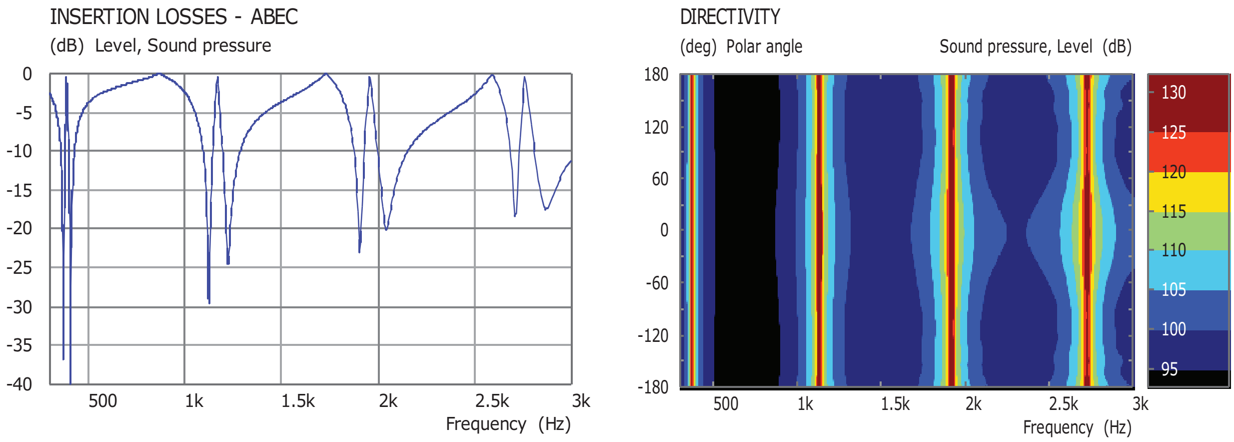
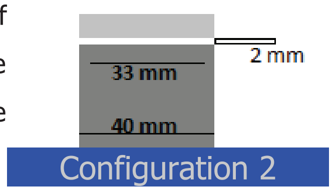


Figure 15. Configuration 2. On left side are insertion losses after installation of rigid disc in front of the waveguide at a distance 1m. On right side is the directivity plot of the acoustic pressure at a distance 300 mm from the end of the waveguide.



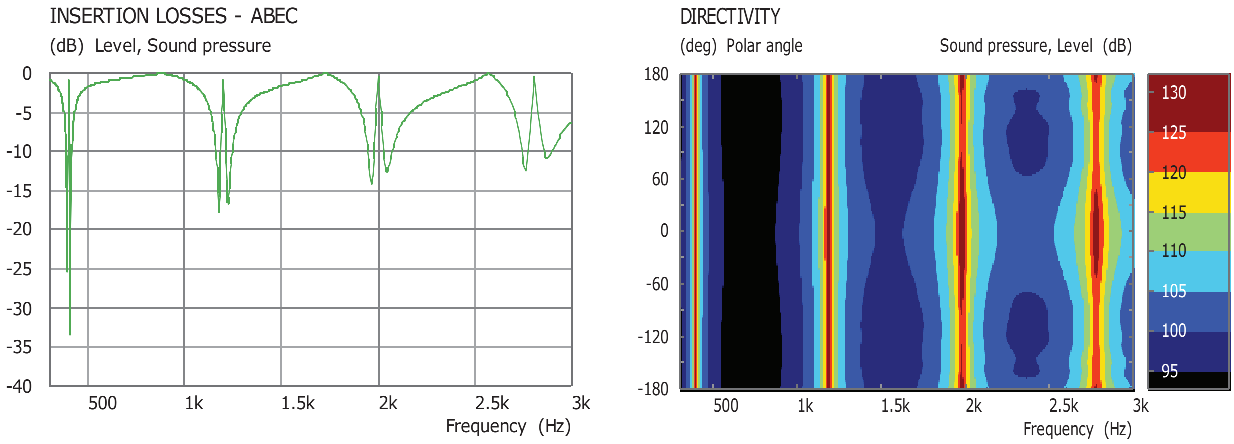
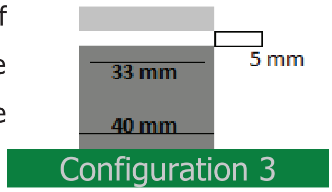
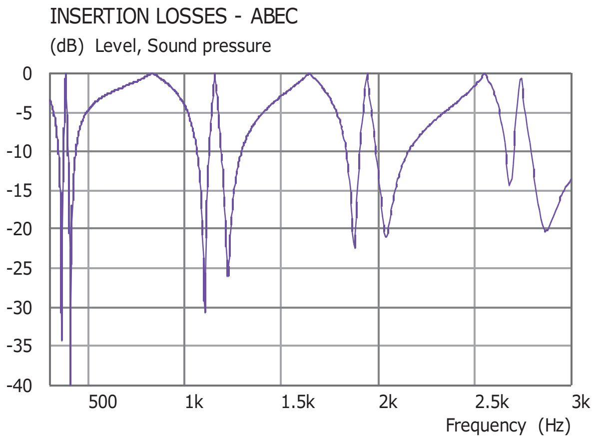
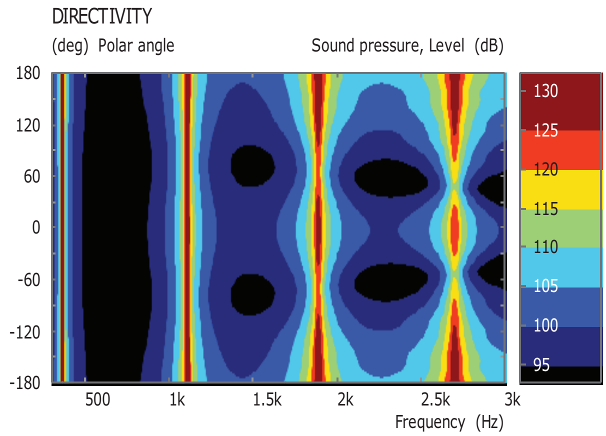


Figure 16. Configuration 3. On left side are insertion losses after installation of rigid disc in front of the waveguide at a distance 1m. On right side is the directivity plot of the acoustic pressure at a distance 300 mm from the end of the waveguide.







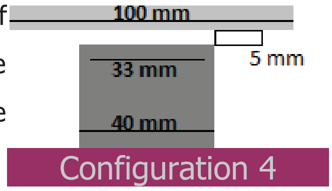


Figure 17. Configuration 4. On left side are insertion losses after installation of rigid disc in front of the waveguide at a distance 1m. On right side is the directivity plot of the acoustic pressure at a distance 300 mm from the end of the waveguide.

4 Study of Waveguides with Damping Elements

The aim of this work is to find how efficient the passive reactive absorbers and the active absorbers are in attenuating of power radiated by the waveguide in comparison with rigid mutes. This is approximately represented by insertion losses. It is also represented by the output acoustical impedance. Optimally its real part should be as low as possible and its imaginary part should stay the same as in the case of waveguide without anything in front of it. The imaginary part of the output acoustic impedance is directly related to resonant frequencies in the input acoustic impedance of the waveguide. Optimally the attenuating system should not shift those resonant frequencies or at least shift them much less than rigid attenuators do. Ten configurations were tested. All those configurations are described in Chapters 3.1.1, 3.1.2 and 3.1.3.

4.1 Measurements

Systems described in chapters 3.2.1, 3.2.2 and 3.2.3. were measured. Measurements of the input and output acoustic impedances were done on laboratory desk in the room of approximate volume 60 m³. Influence of room on measurements was minimal, because the acoustic pressure at spot where the measuring microphones were placed was acoustic pressure excited by the waveguide driver much higher than the acoustic pressure caused by reflections and ambient noise. Measurements of insertion losses were done in the anechoic chamber. Photography of workplace is in Figure 18.

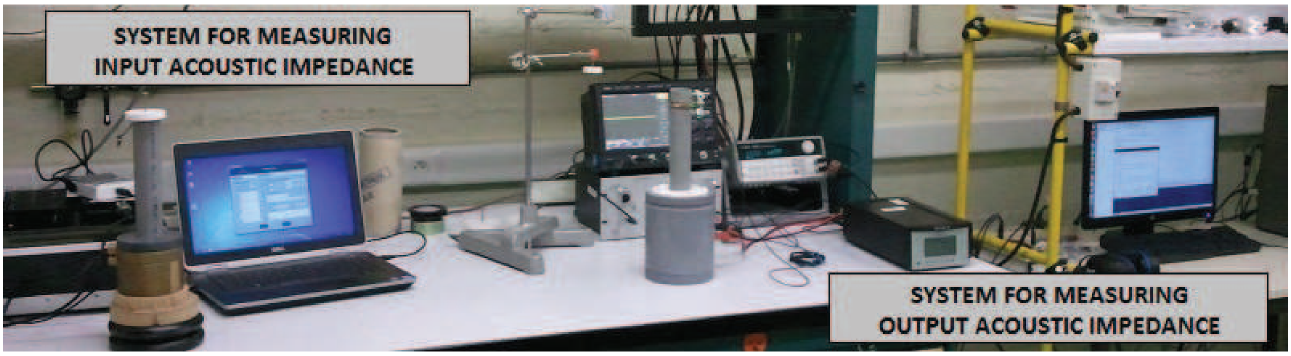


Figure 18. Photo of experimental system

4.1.1 Rigid attenuator

Three configurations with rigid attenuator and one configuration without anything in front of tube waveguide were tested. Input acoustic impedance was measured by the input impedance sensor, which was developed here on Université du Maine. The output acoustic impedance was measured by system described in Chapter 3.2.2. Insertion losses were measured as well. Those losses were measured in the anechoic chamber. The measured input acoustic impedance of tested configurations was compared with the input acoustic impedance of tested configuration simulated in ABEC. The bigger in diameter or closer to the tube waveguide end rigid attenuator was, the bigger influence on the input acoustic impedance it had. Insertion losses were much more affected by the rigid attenuator diameter than by its proximity to the tube end. By placing the rigid disc in front of the waveguide, the acoustic impedance in the end of the waveguide changed. That caused, that the waveguide behaved as it was a bit longer. Effect of that is that the resonant frequency of the waveguide is lower than without the rigid disc. We can also imagine that the system have characteristics between the tube with open end and the tube with shorted end. The resonant frequency of the waveguide is the frequency on which the waveguide has the highest input acoustic impedance. It is expected, that the bigger the rigid mute in diameter is, or closer to the waveguide the rigid mute is, the lower these resonant frequencies should be. It is also expected, that real part of the input acoustic impedance will be lower in that case. It means that the rigid mute in the end of the waveguide behaves like acoustic mass. That will cause a reduction of acoustic pressure radiated by the waveguide (especially on high frequencies).

4.1.1.1 Input Acoustic Impedance

Four configurations, which are described in Chapter 3.1.1 were compared. In Figure 19 the real and imaginary parts of the input acoustic impedances of tested configurations were compared.

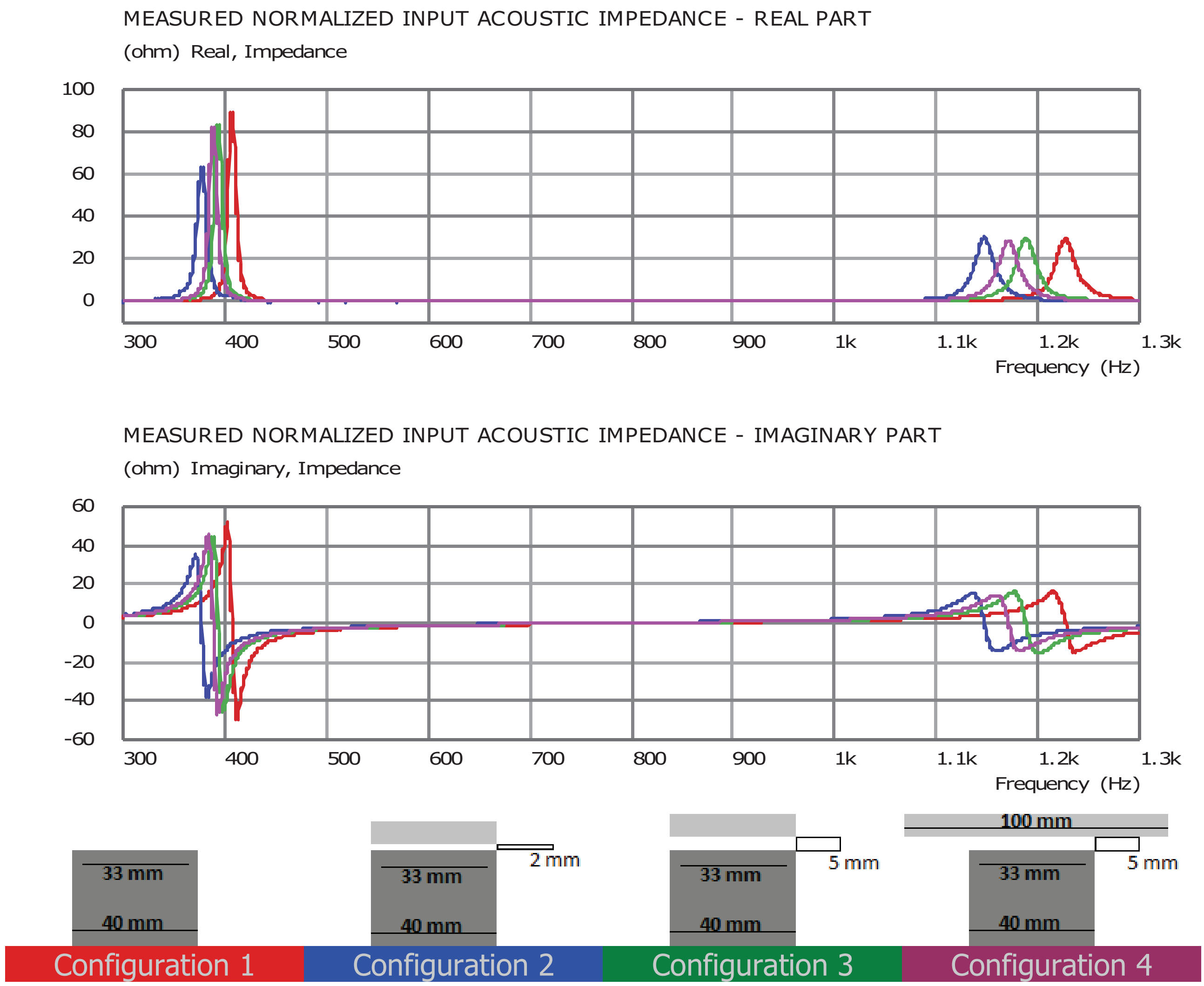


Figure 19. Measured input acoustic impedance (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.1.2 Output Acoustic Impedance

Four configurations described in Chapter 3.1.1 were compared. In Figure 20 the real and imaginary parts of the output acoustic impedances of tested configurations were compared.

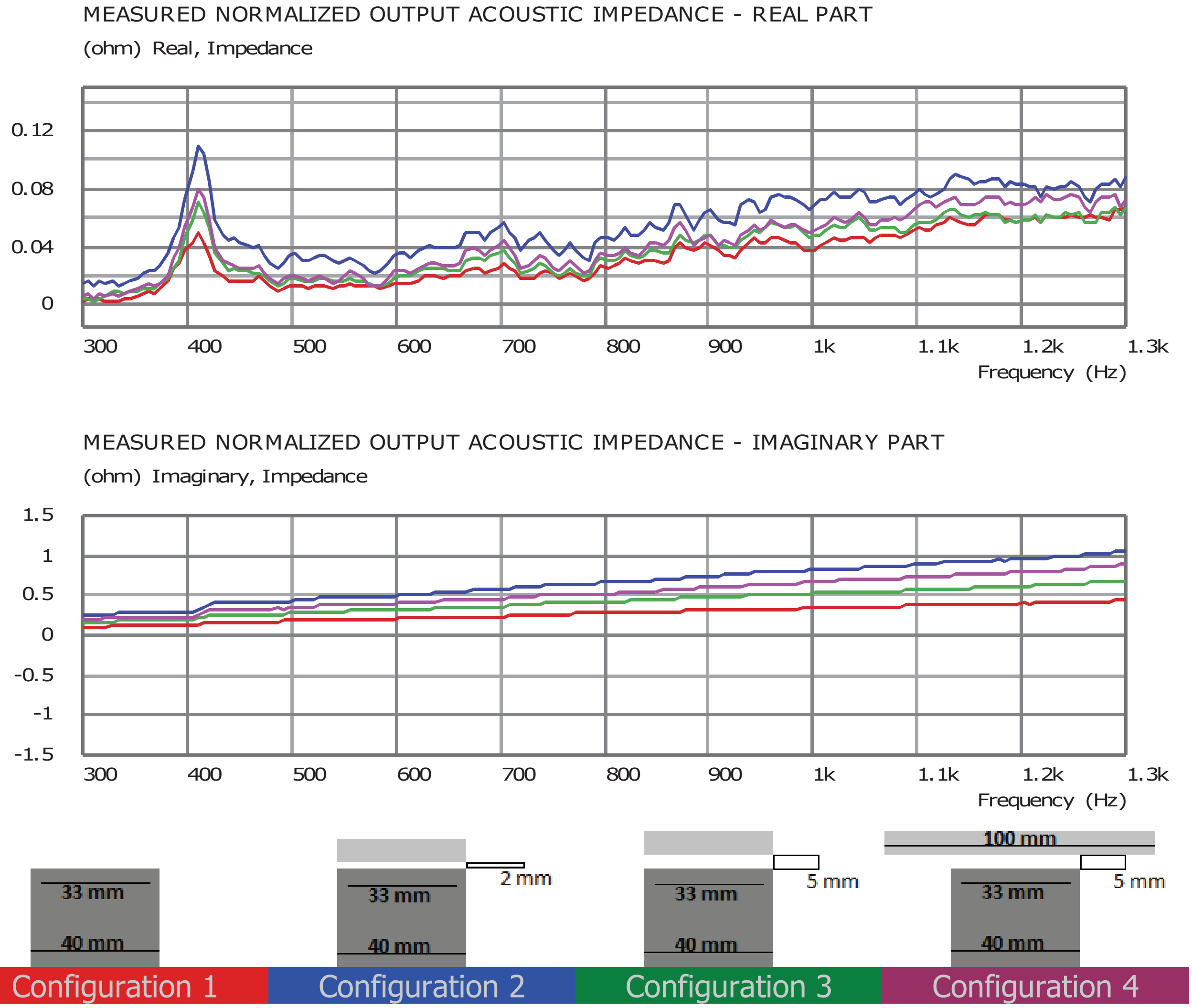


Figure 20. Output acoustic impedance estimated from two measured acoustic pressures (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.1.3 Insertion Losses

Four configurations described in Chapter 3.1.1 were compared. In Figure 21 is shown the difference in the acoustic pressure between configuration without any rigid discs with configurations with rigid discs at a distance of 100 cm from the end of the waveguide.

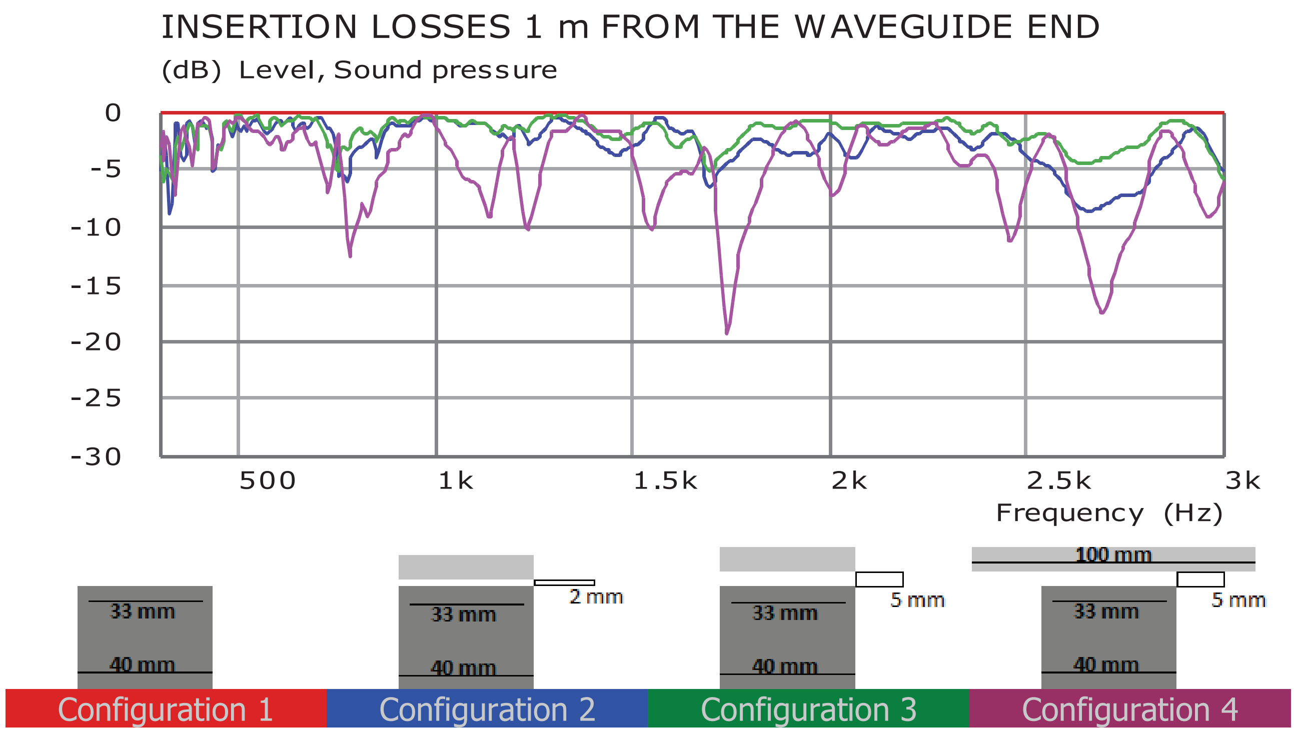


Figure 21. Attenuation of acoustic pressure at 1 m from the end of the tube waveguide (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.2 Passive Reactive Absorber

In this chapter the same measurements of the input and output acoustic impedances and insertion losses as in Chapter 4.1.1 were made. The difference is that rigid disc was replaced by the speaker. In two cases the speaker was in the closed enclosure (ones with shorted connectors and ones with open connectors) and in two cases without the enclosure (ones with shorted connectors and ones with open connectors). The input and output acoustic impedance of all configurations was almost the same (resonances in the input acoustic impedance were just slightly closer to the input acoustic impedance of the configuration with open tube end when the speaker was in the enclosure). Big difference was in the attenuation – the maximal attenuation of configurations with enclosure was about 19 dB (much better than any rigid disc) and maximal attenuation of configurations without the enclosure is just about 11 dB (on par with configuration with the biggest tested rigid disc). Load connected to speaker connectors had very small influence. Slightly better results were achieved with open contacts.

4.1.2.1 Input Acoustic Impedance

Five configurations described in Chapter 3.1.1 were compared. In Figure 22 the real and imaginary parts of the input acoustic impedances of tested configurations were compared .

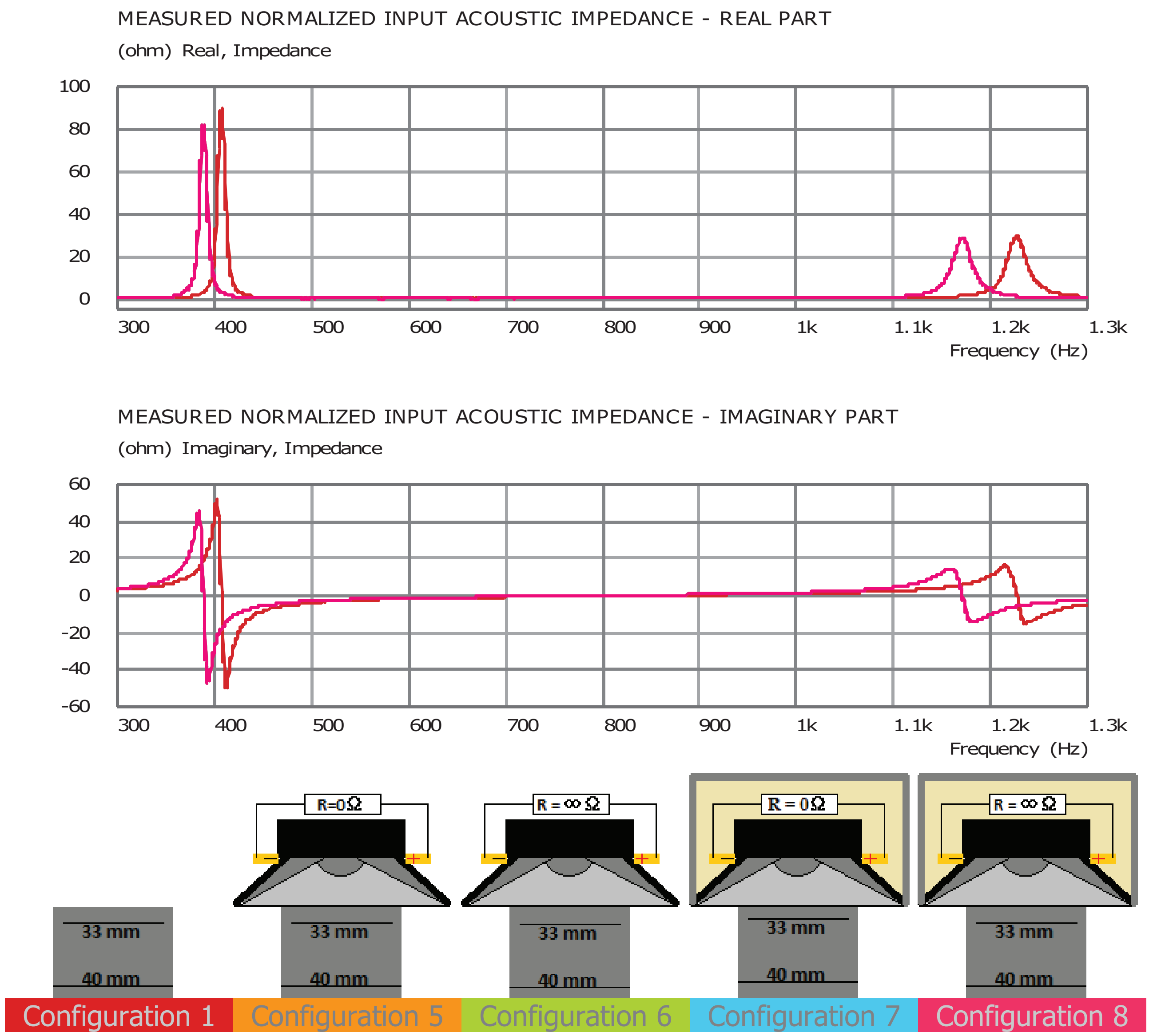


Figure 22. Measured input acoustic impedance (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.2.2 Output Acoustic Impedance

Five configurations described in Chapter 3.1.1 were compared. In Figure 23 the real and imaginary parts of the output acoustic impedances of tested configurations were compared.

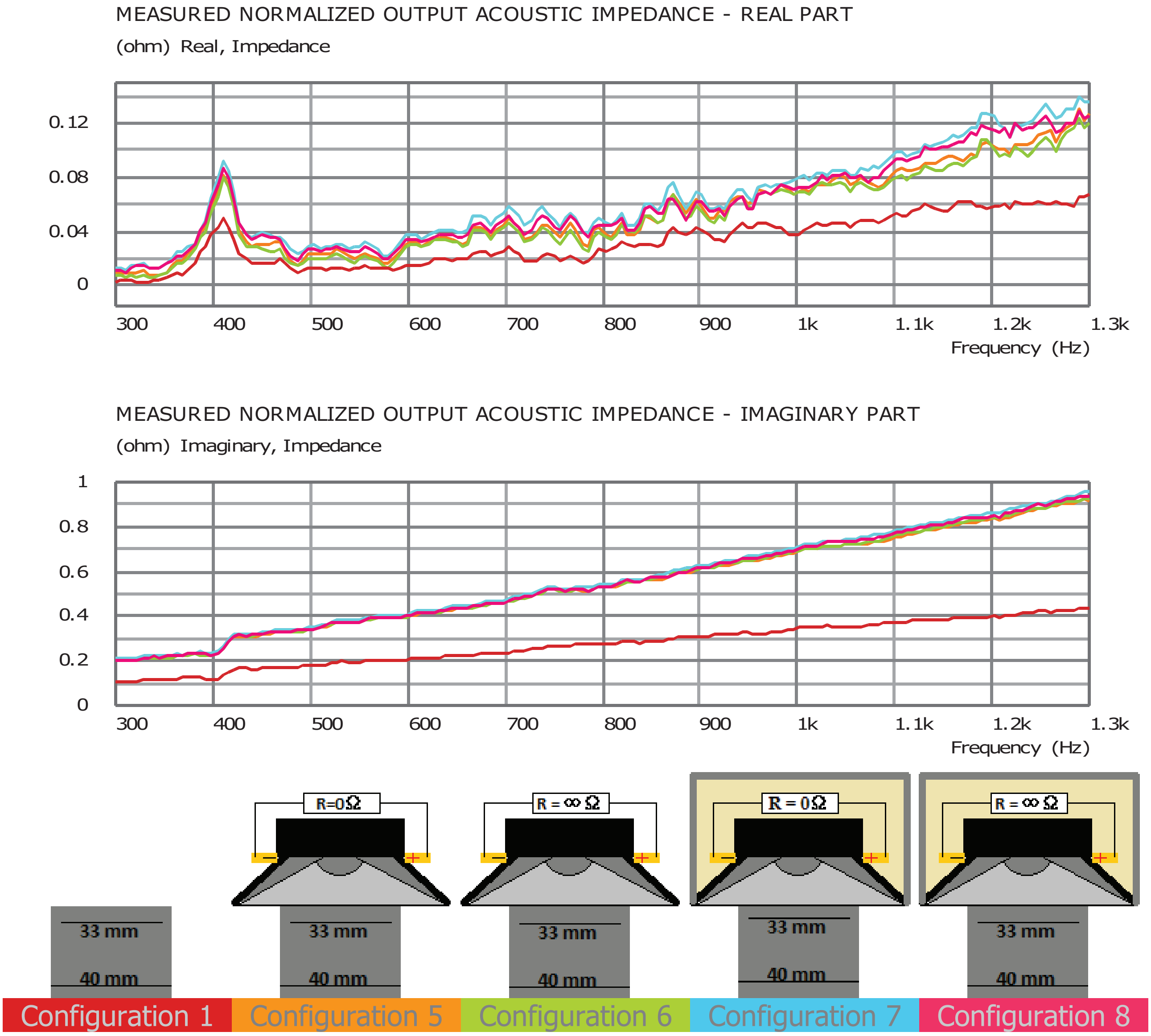


Figure 23. Measured output acoustic impedance (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.2.3 Insertion Losses

Five configurations described in Chapter 3.1.1 were compared. In Figure 24 the difference in the acoustic pressure between configuration without any rigid discs with configurations with rigid discs in distance of 100 cm from the end of the waveguide was shown.

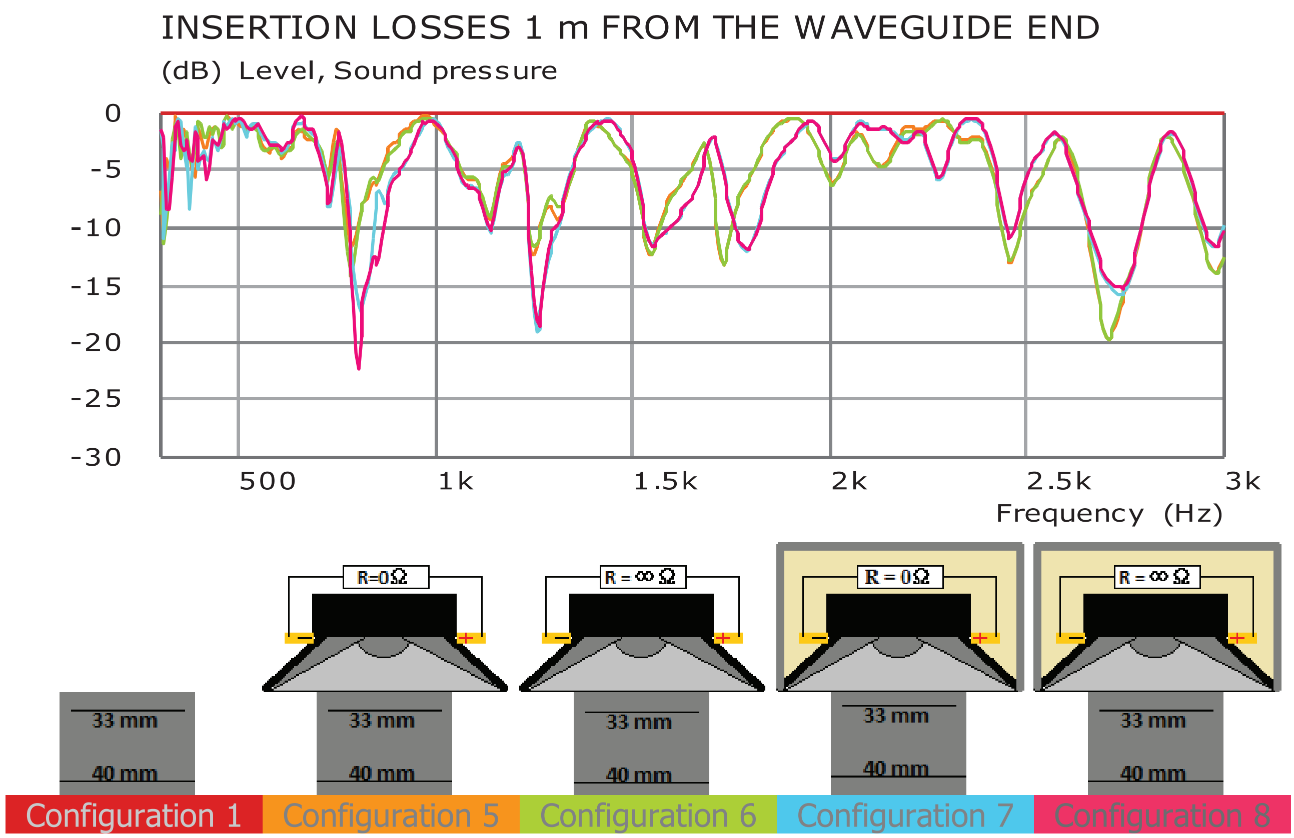


Figure 24. Attenuation of acoustic pressure in 1 m from the end of the tube waveguide (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.3 Active Absorber

A simple active control system was designed, constructed and implemented. For measuring of the input and output acoustic impedance and the insertion losses the same equipment as in Chapters 4.1.1 and 4.1.2 and same speakers as in Chapter 4.1.2 were used. Two configurations were tested – in the first speaker without the enclosure was used and in the second speaker with it was used. Gain of the feedback loop was set just slightly below the level on which system became unstable. Resonances in the input acoustic impedance were close to same for both configurations and little bit closer to the input acoustic impedance resonance of open tube than configurations from Chapter 4.1.2. Unfortunately in this case the input impedance sensor did not produce acoustic level high enough to make ACS system to have some influence on the input acoustic impedance. Attenuation of the configuration without enclosure was really low in the tube axis, but subjectively at the plane which is perpendicular to the tube axis was attenuation higher than in case of the passive systems. Anyway the best result was achieved with configuration with the enclosure. Maximal attenuation of this configuration was in tube axis about 22 dB, but attenuation was subjectively much higher than in case of any passive system.

4.1.3.1 Input Acoustic Impedance

Three configurations described in Chapter 3.1.1 were compared. In Figure 25 the real and imaginary parts of the input acoustic impedances of tested configurations were compared.

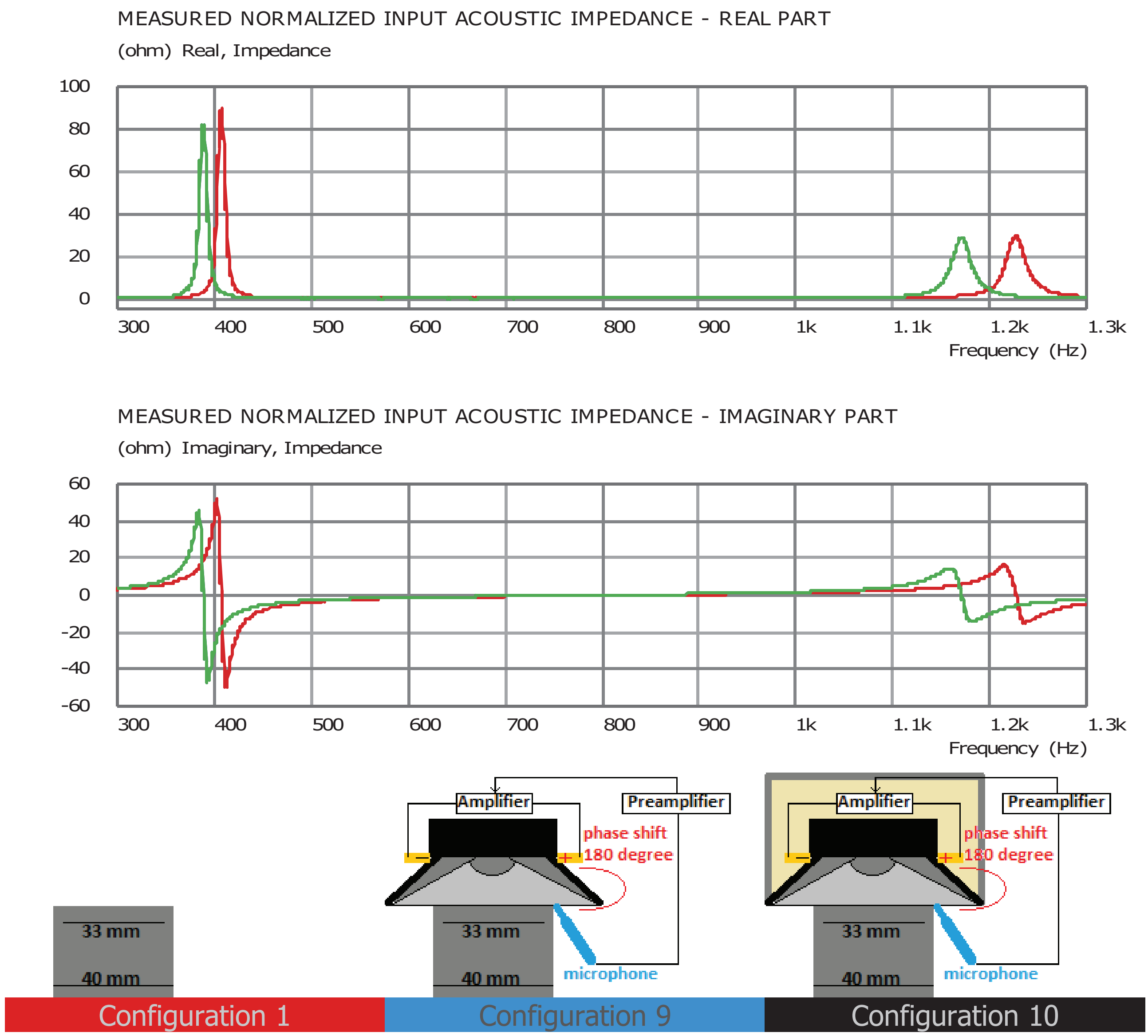


Figure 25. Measured input acoustic impedance (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.3.2 Output Acoustic Impedance

Three configurations described in Chapter 3.1.1 were compared. In Figure 26 the real and imaginary parts of the output acoustic impedances of tested configurations were compared.

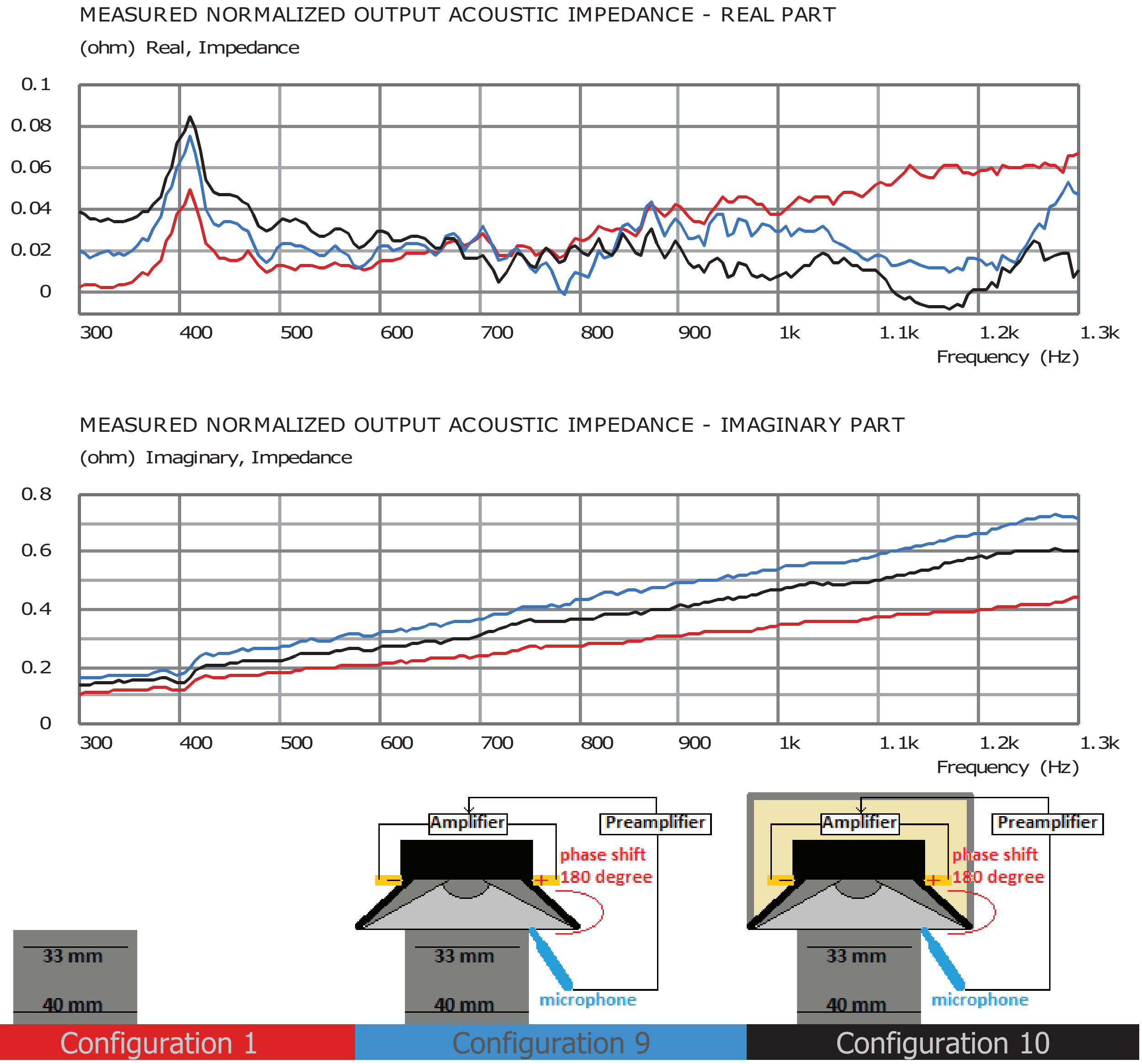


Figure 26. Measured output acoustic impedance (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.1.3.3 Insertion Losses

Three configurations described in Chapter 3.1.1 were compared. In Figure 27 the difference in the acoustic pressure between configuration without any rigid discs with configurations with rigid discs in distance of 100 cm from the end of the waveguide was shown.

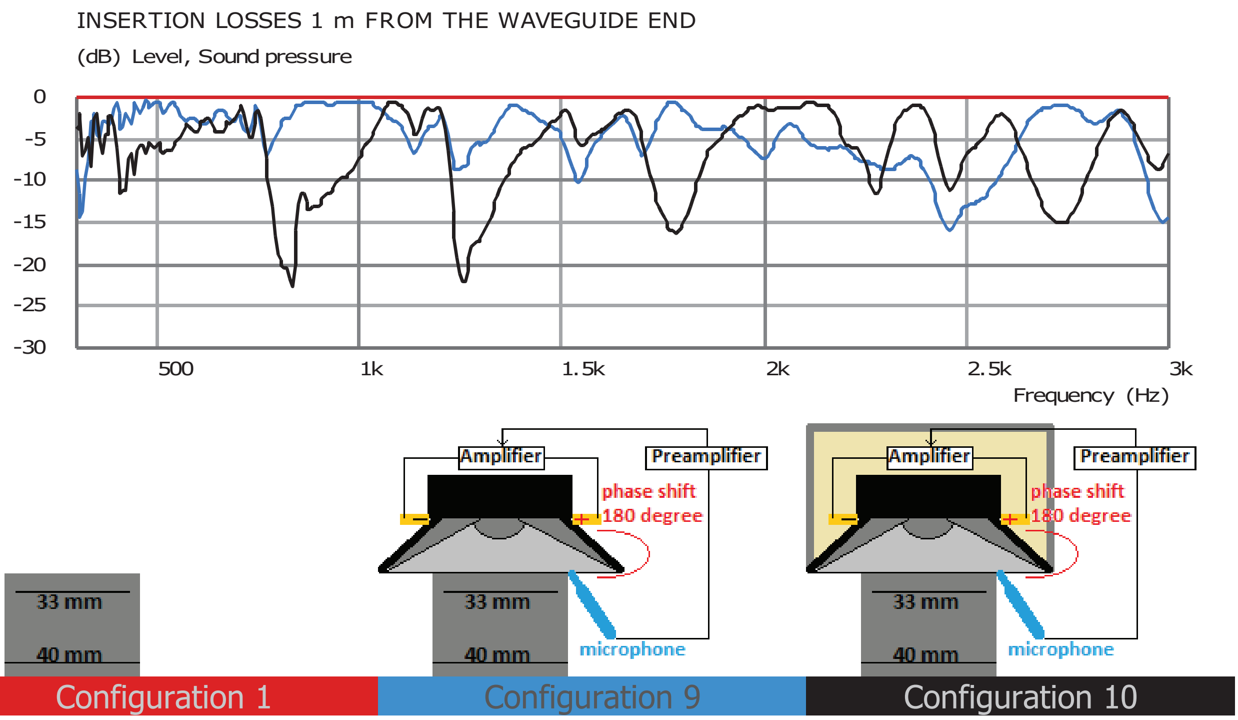
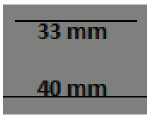
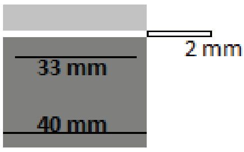
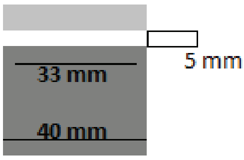
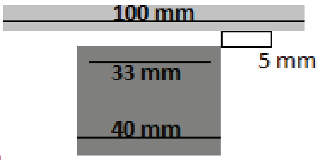
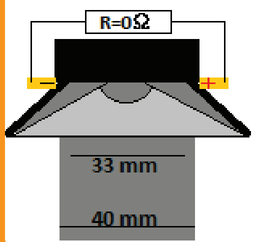
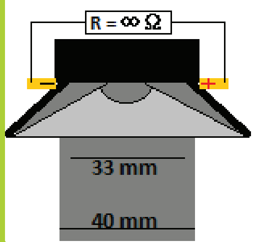
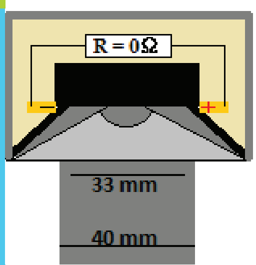
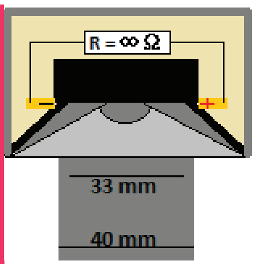
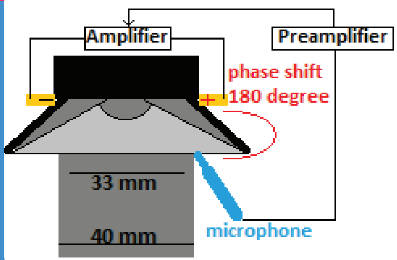
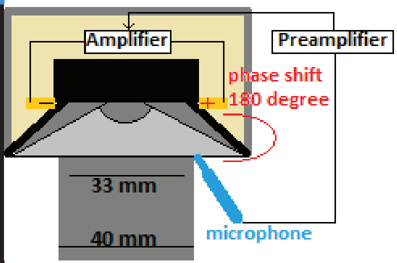


Figure 27. Attenuation of acoustic pressure in 1 m from the end of the tube waveguide (different configurations are given in the sketch above). The total waveguide length is 20 cm.

4.2 Results

Table with results of all tested configurations.

	Configuration	f_{inrez1} (Hz) A (Hz) B	Z_{inrez1} [Real] (Ω) A (Ω) B	$Z_{out1kHz}$ [Real] (Ω) A (Ω) B	$Z_{out1kHz}$ [Imag] (Ω) A (Ω) B	Att_{max} (dB) (Hz)	Att_{rez1} (dB)	Att_{avg} (dB)
Configuration 1		407 403	63.2 26.8	0.032 0.026	0.165 0.245	0	0	0
Configuration 2		377.3 371	45.2 34	0.044 0.048	0.458 0.583	8.1 2665	1.2	2.8
Configuration 3		393.5 392	59 34	0.035 0.034	0.291 0.275	6.7 234	2.3	1.8
Configuration 4		389.3 384	57 47	0.034 0.036	0.359 0.472	14.4 2700	1.7	5.1
Configuration 5		388.5 384	58 32	0.034 0.048	0.359 0.488	16.2 2700	4	5.4
Configuration 6		388.5 384	58 32	0.034 0.049	0.359 0.490	15.9 2700	2.4	5.4
Configuration 7		388.3 382	58 36	0.033 0.057	0.359 0.504	16.2 812	2.4	5.6

Configuration 8		388.3 383	58 36	0.033 0.051	0.359 0.497	18.3 804	2.5	5.6
Configuration 9		388.3 393	58 23	0.033 0.021	0.359 0.385	13.9 2475	1.6	4.8
Configuration 10		388.5 400	58 18	0.033 0.006	0.359 0.333	20.7 820	6.2	6.8

Tab 2. Comparison of tested configurations. Attenuations were read from logarithmically smoothed graph (with relative window width in ten parts of octave), numbers signed as A were read from graphs estimated from measured input acoustic impedance and numbers signed as B were read from graphs estimated from two measured pressures. Measured input acoustic impedances of configurations 9 and 10 are inaccurate, because sensor does not produce acoustic level high enough to make ACS work.

4.2.1 Discussion of Measurements

Ten different configurations were tested. One was composed just from the straight cylindrical waveguide and the remaining nine were composed from the same cylindrical waveguide and different attenuators in front of it. In three cases the attenuator was the rigid disc, in four cases the attenuator was the passive reactive absorber and in two cases the attenuator was the active system with feedback loop. The input and output acoustic impedance of those configurations and attenuation of nine of them were tested. From configurations with the rigid disc were get the best results configuration with 100 mm disc diameter 5 mm far from the waveguide end (Configuration 4), which had the best average insertion losses 5.1 dB (in 300 - 3000 Hz band) and the first resonant frequency shift about 18 Hz (4.4 % of f_{res} without any object in front of the waveguide). From configurations with passive reactive absorber the best results achieved the configuration with speaker placed in enclosure with no electric load (Configuration 8, configuration with enclosure with shorted connectors was just slightly worse). It had average insertion losses 5.6 dB (in 300 - 3000 Hz band) and the first resonance frequency shift 17 Hz (4.2 % of f_{res} without any object in front of the waveguide). Configurations without enclosure had much lower insertion losses. Even better results were achieved with the active absorber with speaker in the enclosure. This configuration had average insertion losses 6.8 dB (in 300 - 3000 Hz band) and the first resonance frequency shift 11 Hz (2.7 % of f_{res} without any object in front of the waveguide).

4.2.2 Comparison between Measurements and Numerical Results

There was a very good correlation between measured input acoustic impedance resonant frequencies of the straight cylindrical waveguide with rigid disc in front of it and modeled one. But there was a big differance in quality factor of those resonancies. It was because the ABEC does not compute with losses inside the tested structure.

4.2.3 Further Work

To achieve even better results the following things should be done :

- Investigate how the system works with a real trumpet that is producing much higher acoustic pressures.

- Measure attenuation in whole space, not only at one point.

- Optimize system to have the biggest attenuation on resonant frequencies of the waveguide (tube and later trumpet, estimate optimal T-S parameters of speaker and optimal distance from tube end).

- Experiment with an error microphone placement to get higher gain (for example to the tube beginning and estimate pressure which is on the output from known transfer function of the waveguide).

- Use more advanced feedback controller (analog with filter, digital with DSP, with compensation of not ideal transfer functions of individual parts of ACS).

5 Conclusion

In this thesis the influence of placing the rigid disc, the passive reactive absorber and the active absorber in front of the straight cylindrical waveguide on its characteristics was studied. Changes were observed in the input and output acoustic impedance and in insertion losses at a distance 1m from the waveguide end. As waveguide the straight cylindrical tube was used.

In the beginning a theoretical research of possibilities of reduction of the acoustical power which is radiated by waveguide was done and the formulas for computing the output acoustic impedance from two pressures measured nearby the straight tube waveguide end were prepared. Those formulas were also verified.

Then the experimental system, which allowed studying of behavior of configuration with the straight tube waveguide without anything in front of it, three configurations with the rigid disc placed in front of the same waveguide, four configurations with the passive reactive absorber placed in front of the same waveguide (testing influence of having absorbing speaker mounted in the enclosure and testing influence of electrical load connected to the absorbing speaker) and two configurations with the active absorber placed in front of the same waveguide (testing influence of having absorbing speaker mounted in the enclosure) was designed. Then the system for measuring the output acoustic impedance of the waveguide and acoustic pressure was designed, set up and calibrated and the system for measuring the input acoustic impedance of the waveguide was used.

From configurations with the rigid disc the best results had the configuration with 100 mm disc diameter 5 mm far from the waveguide end , which had average insertion losses 5.1 dB (in 300 - 3000 Hz band) and the first resonance frequency shift about 18 Hz (4.4 % of f_{res} without any object in front of the waveguide). From configurations with the passive reactive absorber the best results achieved the configuration with speaker placed in enclosure with open connectors (configuration with enclosure with shorted connectors was just slightly worse). It had average insertion losses 5.6 dB (in 300 - 3000 Hz band) and the first resonant frequency shift 17 Hz (4.2 % of f_{res} without any object in front of the waveguide). Configurations without enclosure had much lower insertion losses. Even better results were achieved with active absorber with enclosure. This configuration had average insertion losses 6.8 dB (in 300 - 3000 Hz band) and the first resonance frequency shift 11 Hz (2.7 % of f_{res} without any object in front of the waveguide).

This work opens a lot of opportunities for further research. It could be investigated how would such system perform on real trumpet, radiated power could be measured in whole space and compared with that one computed from the output acoustic impedance. The influence of system physical dimensions on its properties and their optimization or improvement caused by usage of more advanced feedback controller could be investigated as well.

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APPENDIX:

Folder structure:

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  - [CONF1_CircSym_outimp]
  - [CONF2_CircSym]
  - [CONF3_CircSym]
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