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Internship Final Report

Measuring the acoustic properties of rocket engine faceplate configurations

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PREFACE

An internship is a part of a master program of Mechanical Engineering studies at the University of Twente. The objective of a project work is to gain a valuable learning. This serves as an opportunity for the student to put his scientific knowledge into practice in an industrial environment. The aim of a student assignment is to find a correlation between an academic background and the work experience that is being offered.

With this goals in mind I spent the period between March and July 2017 at the German Aerospace Center (DLR), located in Lampoldshausen. I was employed by Institute of Space Propulsion as a member of the Combustion Dynamics Research Group. I have chosen this Institute because of their commitment in a space industry and its role as an international partner and competitor. The most attracting part, is that the DLR Institute transfer knowledge and technological advances into space field, which makes company competitive in the market-place.

This report serves as an overview of the work I performed during the stay. The main task was to develop a modified version of an impedance tube for measuring the damping properties of porous injector for rocket engines, designed at DLR Lampoldshausen.

I would like to express my sincere gratitude to all the people who contributed in some way to my work described in this paper. First of all I would like thank to a Justin Hardi who was my supervisor during the internship period and his useful feedback in order to determine the direction of this research. I am also grateful for the support and many valuable discussion given by Wolfgang Armbruster. Looking back from my internship, I can say that it has been a valuable and truly amazing experience. The working environment and the people at the DLR are really great and they were the ones who gave motivational spirit to carry on prospective career.

Rafal Kurylek

Lampoldshausen, July 2017

Table of Contents

1. Introduction

The high-frequency combustion instability during an ignition process has a great influence on correct operation of combustion process and combustion chamber itself. This type of instabilities is considered to be the most destructive, and is usually characterized by well-defined frequencies and mode shapes corresponding to the acoustic modes of the chamber. Understanding and predicting acoustic instabilities in liquid propellant rocket engine requires the knowledge of the acoustic behavior of all the elements feeding the combustion chamber [1].

Difficulties can arise from a concerning about fundamental mechanisms and the coupling dynamics, leading to combustion instabilities. This can emerge from the presence of many diverse phenomena such as non-steadiness generated by pure fluid turbulence, or combustion processes themselves. From a literature survey we can assume that coupling of unsteady heat release and the chamber acoustic can lead to pressure resonance. That certain amount of distortions of a pressure are observed at any location in the chamber. Similarly fluctuation of the temperature and velocity can also be considered[2].

Minor oscillations can negatively affect performance capabilities and can lead to engine failure. If certain mode excited by flow and combustion match structural modes of engine, strong oscillations can be excited.

Consequently, the motivation behind the present work was to gain further insight into key parameters associated with acoustic characteristic of the material components in broad frequency range. This data are crucial for implementation of boundary values in the simulation of combustion instabilities within rocket combustion chamber. Using these values we can achieve accurate simulation of combustion processes in rocket combustion chamber [1].

This paper shows the construction of an acoustic measurement system for the materials leading to an estimation of a complex reflection factor at normal sound incidence, based on the impedance tube prototype and the development of an algorithm that relate the signals of two microphones of the system. The method of calculation, construction and measurement are based on the procedure recommended by the ISO10534-2, which reaches a transfer function between two signals of sound pressure measures in an impedance tube.

The goal of this report is to find a reproducible method of measuring the frequency dependent acoustic behavior of a material probe. A repeatable model analysis method will be proposed in order to determine characteristic parameter. Then this will be investigated for multiple type of material specimens. Characteristic behavior will have to be found for a sintered bronze disk material, rigimesh wire plate and foam. To check correctness of the operation the open-end and closed end boundary condition will be established.

1.1. Location Lampoldshausen

DLR Lampoldshausen is a home for a Institute of Space Propulsion, one of the key space research facilities. It also plays integral role in the European space flight program and preserve unique expertise in developing and operating engine test facilities. A number of other companies and institute also make use of the site’s services and test benches. These include agencies ESA, CNES, Snecma and space company as EADS Astrium. The location comprise five departments: Rocket Propulsion, Test facilities, Engineering, Propellants and Safety, Quality and Facility Management.

Engineering and operation departments together with a research department deliver results from the early stage of the project development up to a final product.

At the different test benches, engines of different sizes and application, can be utilized, developed, qualified and tested. To a various altitude simulation facilities it is possible to include the satellite and upper stage engine bench P1.0, the cryogenic and storable upper-stage engine facilities P4.1 and P4.2, where since 2005 the facilities has been performing development test for Vinci engine under vacuum condition. The P5 facilities are utilize to test main stage engine of Ariane 5 launcher, namely Vulcain 2. Knowledge about nozzle and thrust chamber design and operation are mainly based on broad investigations carried out at the cold-flow facility P6. For a research of high-pressure combustion with hydrogen and oxygen, test facility P8 is used. The test facility is able to operate under a wide range of conditions considering the mass flow and the supply pressure at the interface to the model combustion chamber. Additionally, in a main test bench, a small scale test facility M3 is used for the basic phenomenological analysis. Test bench M3 is designed for investigating high frequency combustion instabilities in laboratory scale rocket combustion chambers, where several propellant combination can be tested under cryogenic or ambient conditions.

Figure 1. Test Facility P4.1 [3]

Figure 2. Test Facility P8 [3]

Despite progress that has been made to understand the combustion process in rockets, combustors itself are still at the main concern. Most of the experimental work within a combustion dynamics group is focusing on determining the interaction mechanism by which energy from the combustion process is transferred into the acoustic energy of the excited mode. This interaction is captured quantitatively in uniquely developed research combustors, using conventional and high-speed optical diagnostics.

By means of the combustion chamber model, which provides realistic conditions for rocket engines, experiments can be carried out. “In-depth” understanding of these processes is a key requirement for designing optimized engines in future. Nowadays, there is several different types of combustions that is utilized. Small scale experimental setup can provide investigation on the interaction of an acoustic wave with combustion. Different method also exist on reconstruction of acoustic pressure field based on dynamic wall pressure measurements. The extended investigation on interaction between combustion and acoustic are performed on BKH, a rectangular combustor. This type of shape support generation of standing transversal waves. Another type of chamber, namely BKD, of a cylindrical cross section, enables to evaluate a spinning modes, often referred to the most critical in rocket application.

1.2. Advanced Porous Injector

The purpose of the following project is to develop a modified version of an impedance tube for measuring the damping properties of a porous injector for rocket engines. At the DLR Institute of Space Propulsion Lampoldshausen, an injector head design is investigated which relies on numerous of advantages toward the well-known shear coaxial injector.

Figure 3. API injector concept [3]

For the new concept, the designed system should fulfill set of general requirements: homogeneous propellant distribution to individual injector elements to allow optimal propellant distribution and mixing, controlled behavior during start-up to guarantee reliable ignition, minimal pressure losses and maximum combustion efficiency.

In comparison to all classical injectors which provides proper atomization and proper injection of the propellants, this concept depends entirely on atomization and mixing, driven by combustion processes inside the thrust chamber – thus allowing for reduced pressure losses within the injection system.

The porous face plate, through which all the hydrogen gaseous are guided to the combustion chamber and the integrated tubes for the liquid oxygen are the primer features of the API concept. Two material are chosen to preserve porous characteristic, namely: sintered bronze (CuSn12-C) and stainless steel wire mesh. Both type of materials possess favorable characteristic, for instance: good machinability, high thermal conductivity, preferable propellant mixing ratio.

2. Basics

This chapter presents the theoretical fundamentals of thermo-acoustic flow instabilities. In this case, the acoustic background is explained in general, as to presents the equation of this physical phenomenon.

2.1. Combustion instabilities

In order to perform accurate simulations of an acoustic vibrations in rocket combustion chambers, the implementation of, as “real” as possible conditions is a very important. The natural frequencies and eigenmodes of the combustion chamber can only become mapped realistically If the boundary conditions maintains the characteristics of the combustion chamber components correctly.

Due to the geometric complexity and complexity of the simulation, large differences in design, the boundary conditions are mostly unknown. The injection planes represent the greatest problem for the simulation. Thus we need to evaluate this boundary experimentally. Instead of doing the characteristics of each geometries separately, the boundary condition can be determined by the acoustic impedance for a whole structural assembly. The impedance tube need to be constructed in such way that it represents a simple and fast way to experimentally determine an acoustic impedance for the improvement of numerical simulations.

2.2. Acoustic theory of cylindrical volume

In acoustic, the variation of the pressure, p, is in an acoustic field, described by a following partial differential equation:

$$\frac{\partial^2 \mathrm{p}}{\partial \mathrm{t}^2} - \mathrm{c}^2 \Delta \mathrm{p}' = 0 \tag{1}$$

the general solution for one-dimensional case of equation which has a propagating and reflection part, has the form:

$$\mathrm{p(x,t)} = \mathrm{p}_+(\mathrm{t} - \frac{\mathrm{x}}{c}) + \mathrm{p}_-(\mathrm{t} + \frac{\mathrm{x}}{c}) \tag{2}$$

Assuming a temporal harmonic pressure change

$$\mathrm{p} = \mathrm{p}_0 \sin(\mathrm{kx} - \omega \mathrm{t});\ \mathrm{k} = \frac{2\pi}{\lambda} = \frac{\omega}{c} = \frac{2\pi \mathrm{f}}{c} \tag{3}$$

Where the following are: c0- speed of sound, λ- wavelength, f- frequency [4].

2.2.1. Reflection, Impedance, absorption,

Throughout this assignment, the term acoustic impedance refers to a specific acoustic impedance. The specific acoustic impedance, z, at a point in a sound field is a quotient of the complex acoustic pressure, ∂p, and complex acoustic velocity, ∂v, at that point:

$$\mathrm{z} = \frac{\partial \mathrm{p}}{\partial v} \tag{4}$$

for a plane progressive sound wave in a fluid, the specific acoustic impedance equals to $\rho_0 c_0$, where ρ_0 is the fluid mass density and c_0 denote the speed of sound. The product of this two quantities is called the characteristic impedance of fluid. For air, $\rho_0 c_0 = 413.55 \frac{\mathrm{kg}}{m^2 s}$; for helium $\rho_0 c_0 = 167.56 \frac{\mathrm{kg}}{m^2 s}$ at normal temperature and pressure conditions.

The specific acoustic impedance at a boundary between a fluid and a material, is a property of the material. For sound wave in a fluid, normally- incident upon a planar boundary, the pressure reflection coefficient, Z, is given by

$$\mathrm{Z} = \frac{Z_{bdy} - \rho_0 c_0}{Z_{bdy} + \rho_0 c_0} \tag{5}$$

where Z_{bdy} is the boundary (normal) specific acoustic impedance and $\rho_0 c_0$ is the characteristic impedance of the fluid.

The absorption factor can be calculated using reflection coefficient:

$$a = 1 - |r|^2 \tag{6}$$

Which finds a great applicability, especially in physics and define degree of acoustic material absorption [5].

3. Impedance tube methods

Several different methods exist to determine the sound absorption coefficient and surface impedance of samples in impedance tubes. The oldest and most time-consuming method is sampling of the standing waves in front of a specimen (the SWR method). Since the Impedance ratios of an material are related to its physical properties, such as porosity, airflow resistance and density, measurements described in this test method are useful in basic research. Similar method, which uses analogous setup is Transfer Function method. This method proposes a quicker way of measurement utilizing the complex transfer function (TF) between two separated microphones. During development of various methods an improved version of transfer function method were proposed. Improvement of method is based on application of a well mounted stationary reference microphone. This method introduce correction factor in order to compensate an acoustic signal time travel between the loudspeaker and the microphone at the position 1 and 2. The necessary information about different technique will be described in the following section.

3.1. Method using standing wave ratio

A method for investigating the acoustic properties with the impedance tube is the Mini-Max method, also known Standing Wave Ratio. This method is standardized in DIN EN ISO 10534-1 and is based on utilization of a portable probe microphones.

A movable microphone registers the standing wave pattern in the impedance tube, for the localization of pressure minima and for the acquisition of sound pressure amplitudes (in the maxima and minima of the standing wave). The structure of the impedance tube for examination with the mini-max method is shown below.

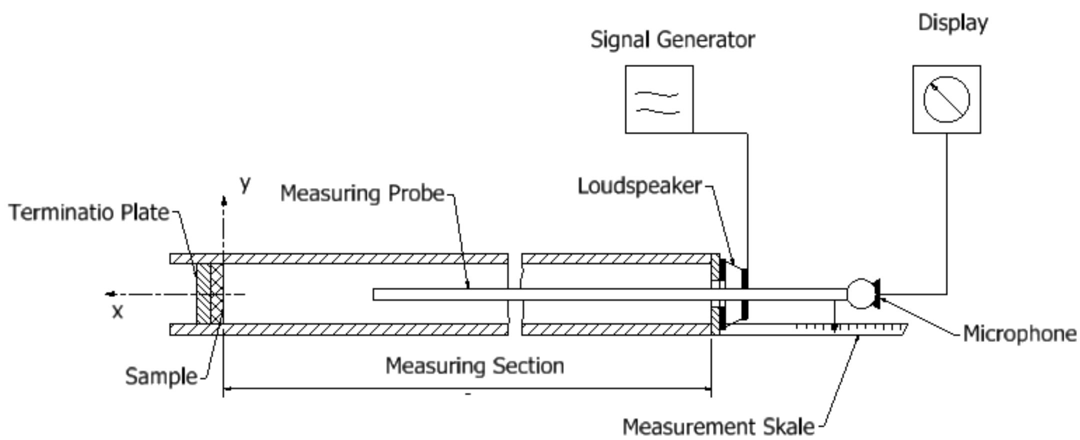


Figure 4. Standing Wave Ratio Measurement Setup [6]

The principle of this methods can be formulated as follows. The test object is mounted at the one end of a straight rigid, smooth impedance tube. The incident plane sinusoidal sound wave p_i is generated by loudspeaker at the other end of the tube. The superposition $\mathrm{p} = p_i + p_r$ of the incident wave p_i with the wave reflected from the test object, p_r produces a standing wave pattern in the tube. As a consequences the measured sound pressure amplitudes in a pressure minima and maxima are evaluated as well as a position of this point. Gathered data are sufficient to determine sound absorption coefficient and surface impedance [6].

3.1.1. The formula

The incidence sound wave p_i is assumed to be a plane, harmonic in time with frequency, f, an angular frequency, ω=2πf, without attenuation and direction along the axis of impedance tube (in positive x-direction)

$$p_i(\mathrm{x}) = p_0 e^{\,\mathrm{j\,k\,x}} \qquad \mathrm{k} = \frac{\omega}{c} = \frac{2\pi \mathrm{f}}{c} \tag{7}$$

where the amplitude p_0 is arbitrary.

The wave which is reflected from the test object having a reflection factor r is then

$$p_r(\mathrm{x}) = \mathrm{r}\, p_0 e^{-\mathrm{j\,k\,x}} \tag{8}$$

The particle velocities of the waves (counted negative in x-direction) are respectively

$$v_i(\mathrm{x}) = \frac{1}{\mathrm{Zo}} p_i(\mathrm{x}) \qquad\qquad v_r(\mathrm{x}) = -\frac{1}{\mathrm{Zo}} p_r(\mathrm{x}) \tag{9}$$

The field impedance (on positive x-direction)in the standing wave is

$$Z(\mathrm{x}) = \frac{p_i(\mathrm{x}) + p_r(\mathrm{x})}{v_i(\mathrm{x}) + v_r(\mathrm{x})} = \mathrm{Zo}\ \frac{p_i(\mathrm{x}) + p_r(\mathrm{x})}{p_i(\mathrm{x}) - p_r(\mathrm{x})} \tag{10}$$

At the reference plane x=0, therefore

$$Z(\mathrm{x}) = \mathrm{Z}(0) = \mathrm{Zo}\ \frac{1+r}{1-r} \tag{11}$$

From which follows

$$\mathrm{r} = \frac{(Z/Zo) - 1}{(Z/Zo) + 1} \tag{12}$$

The sound absorption coefficient, a, for plane wave is

$$a = 1 - |\,r\,|^2 \tag{13}$$

where |…| indicates the magnitude of complex quantity.

If the reference plane is in surface of a flat plane object, these quantities are surface impedance, the reflection factor (for normal sound incidence) and the absorption coefficient of the test object.

A pressure maximum in the standing wave occurs when **pi** and **pr** are in phase, i.e.

$$|\mathrm{p}_{max}| = |\mathrm{p}_0|\,(1 + |\,\mathrm{r}\,|) \tag{14}$$

A pressure minimum occurs when they are in opposite phases

$$|\mathrm{p}_{min}| = |\mathrm{p}_0|\,(1 - |\,\mathrm{r}\,|) \tag{15}$$

Using the standing wave ratio

$$s = \frac{|\mathrm{p}_{max}|}{|\mathrm{p}_{min}|} \tag{16}$$

Then

$$s = \frac{1+|\,\mathrm{r}\,|}{1-|\,\mathrm{r}\,|} \text{ and}$$

$$|\mathrm{r}| = \frac{\mathrm{s}-1}{\mathrm{s}+1} \tag{17}$$

Sound absorption coefficient follows from aforementioned equations with a measured amplitudes $|p_{max}|$ and $|p_{min}|$ at a given frequency.

If the sound pressure in the impedance tube is measured in a logarithmic scale(in decibels), and the difference in level between the pressure maximum and the pressure minimum is $\Delta L, dB$, then

$$s = 10^{\Delta L/20} \tag{18}$$

The sound absorption coefficient can be described as:

$$\alpha = \frac{4 \times 10^{\Delta L/20}}{(10^{\Delta L/20} + 1)^2} \tag{19}$$

the phase angle Φ of the complex reflection factor

$$r = |r| e^{j\phi} \tag{20}$$

follows from the phase condition for a pressure minimum in the standing wave

$$\phi = \pi \left(\frac{4\, x_{min,n}}{\lambda o} - 2n + 1 \right) \tag{21}$$

for the n^{th} minimum in front of reference plane

3.2. Transfer function method

More efficient way to obtain an acoustic parameters of a material is to use an impedance tube and two microphones mounted to the wall at the specific points location. This method even works using the same principle it utilize different measurement technique.

The difference is that two microphones at a separate distance are mounted into the wall of the impedance tube at two different locations. As previously stated, plane wave is generated in a tube by noise source, but the decomposition of interfering waves are obtained thanks this two microphone measurement. by means of this , the pressure peaks on the tube wall can be clearly examined. Afterwards the complex acoustic transfer function can be specified. Later made mathematical transformations, lead to determination of basic acoustic parameters. More precise description of the Transfer function methodology can be found in DIN EN ISO 10534-2 [7].

The apparatus for measurement acoustic coefficient is shown in Figure 5.

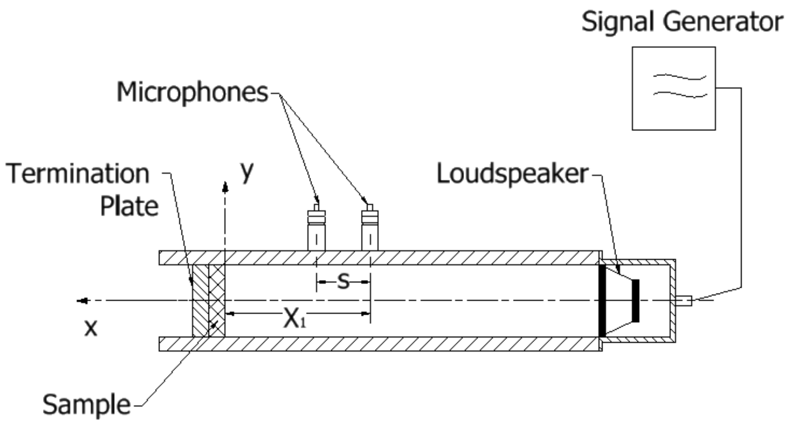


Figure 5. Transfer Function Measurement Setup [7]

The transfer function H_{12} is determined directly with a matched microphone pair by the two microphone. For calculating these, also the calibration method is provided by means of correcting the calculated transfer function for mismatch in amplitude and phase response of two measured channels and different microphone setup. The core of this methods lies in repeated measurement with impedance tube, and also at the same time interchanging the microphone location between each other. Whit this we can evaluate partial transfer function. The transfer functions $\mathrm{H}_{1,\,LP}$ and $\mathrm{H}_{LP,\,2}$ are measured sequentially. Measurement of the following two transfer function require the same mathematical algorithm for both. The corrected transfer function then results:

$$\mathrm{H}_{12} = \sqrt{\mathrm{H}_{1,LP}\,\mathrm{H}_{LP,2}} = |\,\mathrm{H}_{12}\,|\,\mathrm{e}^{j\Phi} \tag{22}$$

Throughout the remainder of this section, a series of equation are presented that represent working expressions based on theoretical sound wave propagation principle.

Assume two pressure signals $p_1(\mathrm{x} = x_1)$ and $p_2(\mathrm{x} = x_1 - \mathrm{s})$ than the quotient p_2/p_1 can be determined. This quotient is also called transfer function in this connection, according to which the investigations are based on this work. The pressure at the two microphone positions are then

$$p_1 = e^{\mathrm{j\,k\,x_1}} + \mathrm{r}\,e^{-\mathrm{j\,k\,x_1}} \qquad p_2 = e^{\mathrm{j\,k\,(x_1 - s)}} + \mathrm{r}\,e^{-\mathrm{j\,k\,(x_1 - s)}} \tag{23}$$

This result in transfer function

$$\mathrm{H}_{12} = \frac{p_2}{p_1} = \frac{e^{\mathrm{j\,k\,(x_1 - s)}} + \mathrm{r}\,e^{-\mathrm{j\,k\,(x_1 - s)}}}{e^{\mathrm{j\,k\,x_1}} + \mathrm{r}\,e^{-\mathrm{j\,k\,x_1}}} \tag{24}$$

If the transfer function is converted according to the reflection factor, the following results can be obtained

$$r = \frac{\mathrm{H}_{12} - e^{-\mathrm{j\,k\,s}}}{e^{\mathrm{j\,k\,s}} + \mathrm{H}_{12}}\,e^{2\mathrm{j\,k\,x_1}} \tag{25}$$

This expression for the reflection factor can be simplified. For this purpose, the transfer function H_{12} is separated into the leading wave H_+ and the reversing wave H_-

$$\mathrm{H}_+ = \frac{p_{2I}}{p_{1I}} = \frac{e^{\mathrm{j\,k\,(x_1 - s)}}}{e^{\mathrm{j\,k\,x_1}}} = e^{-\mathrm{j\,k\,s}} \tag{26}$$

$$\mathrm{H}_- = \frac{p_{2R}}{p_{1R}} = \frac{re^{-\mathrm{j\,k\,(x_1 - s)}}}{re^{-\mathrm{j\,k\,x_1}}} = e^{\mathrm{j\,k\,s}} \tag{27}$$

If this two simplification are used the equation for reflection factor can be formulated as follows:

$$r = \frac{\mathrm{H}_{12} - \mathrm{H}_+}{\mathrm{H}_- + \mathrm{H}_{12}}\,e^{2\mathrm{j\,k\,x_1}} \tag{28}$$

To determine the sound absorption coefficient the following equation is specified

$$a = 1 - |r|^2 \tag{29}$$

It can be clearly noted, only single frequencies can be investigated in the Standing Wave Ratio method. On the contrary, the transfer function method can be stimulated with wide-band noise and thus the acoustic properties can be examined over several frequencies [8].

3.3. Modified transfer function method

An explicit method to measure the acoustic parameters of absorber material in impedance tube were proposed by Krüger [9]. He stated that, even if adequate method to compensate an systemic errors of two signal path are proposed it cannot solve a problem that arise from the travel time t_L of the acoustic signal between the loudspeaker and the microphone at the positions 1 and 2, respectively. During this time the microphone does not receive relevant data from the noise source and the coherence between both signals drops. If t_L is long compared with whole measurement time t_M, the result will be more and more corrupted (due to the delay effect).

The problem can be solved almost entirely by the introduction of a reference microphone at a fixed position M0 which samples the sound field near the first microphone position:

This yields three major advantages:

- The acoustic delay t_L is decreased substantially and the coherence is increased.
- The partially non-linear transfer function of the loudspeaker is excluded from the signal path.
- Both signals come from microphones and are in the same dynamic range which leads to an easier signal processing.

The transfer function H_{12} is calculated from the two TF between the reference microphone at the position M_O and the microphone at the positions 1 and 2, respectively

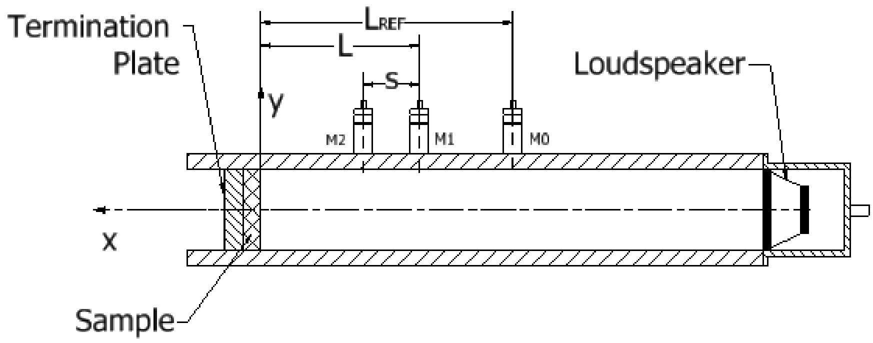


Figure 6. Modified Transfer Function Measurement Setup [8]

$$\mathrm{H}_{12} = \mathrm{H}_{10} \cdot \mathrm{H}_{02} \tag{30}$$

Since systematic errors are again compensated by the sequential measurement procedure, the reference microphone does not have to be of very high quality. The advantage of the simplicity of this method, therefore, remains even for the modified single microphone FFT method.

4. Selection guide for measurement setup

Preparation of the test setup is conducted based on the specification included in the ISO 10534-2 Norm. The details of the instrumentation used during the experiment can be found in the following chapter. Based on above norm the required measurement setup can be listed as follows: Impedance tube, test-sample holder, microphone, signal processing equipment, loudspeaker, signal generator. Choice of the accessories are based on suitability for many future applications. To obtain this every instruments should also have performed calibration tests. They are designed to make a measurements simple, reliable and to provide an accurate and repeatable measurements.

4.1. Impedance tube

Geometrical parameters for an impedance tube are conditioned by evaluation of the standing wave pattern of a plane wave in a tube, which is generated by superposition of an incident sinusoidal plane wave with a plane reflected from the test object. The component is essentially a circular shape duct with a test sample holder on one side and a sound source on the other. To prevent occurrence of errors, the design should have possess some specific characteristic. The duct should retain an uniform cross-section with a straight and smooth walls. The structural resonance frequencies might have appear within a working range, thus the wall thickness should be chosen properly of about 5% of cross- dimension. For a whole measurement procedure the air tightness of duct should be preserved.

The design of a duct itself has an great influence on the experiment parameter namely working frequency range. The working frequency range is determined by length of a tube and internal diameter. The working frequency range is f and can be denoted as follow:

$$\mathrm{f}_l < \mathrm{f} < \mathrm{f}_u \tag{31}$$

where fl- lower working frequency of a tube is limited by accuracy of a signal processing equipment, and fu- is chosen to avoid the occurrence of non-plane wave mode propagation.

The condition for f_u is:

$$\mathrm{f}_u\,\mathrm{d} < 0.586\,\mathrm{c}_0 \tag{32}$$

This condition are valid for circular tube with inside diameter d [m] frequency range f_u [Hz] and speed of sound c_0 [m/s] for a specific medium.

Obtained upper limit frequency parameter is used to evaluate the spacing between the microphone. The experimental guide states the microphone spacing should exceed 5% of the wavelength corresponding to lower frequency of interest provided that the following equation is satisfied:

$$\mathrm{f}_u\,\mathrm{s} < 0.45\,\mathrm{c}_0 \tag{33}$$

4.2. Test-sample holder

Different type of specimen holder might be necessary to perform a test. This difference depends on type of specimen, thickness and diameter. Nevertheless, some general features need to be fulfilled. It should be possible to check the position and flatness of the front surface. For a various adapter the placing of a heavy backing plate behind specimen also should be affordable. The purpose of such plate is to create a sound-reflective termination, thus it also should be tightly attached to the impedance tube flange. The detachable holder need to be properly sealed and confirm with interior shape and dimensions of main part of impedance tube.

4.3. Microphone adapter

The most important aspect of positioning the microphone, is to attached the diaphragm flush with the interior surface of the tube. adapter is used for this. Construction of apparatus can be done in such a way that contain every mounting point of microphone. Special construction with a base plate and plugs can be attached to the tube by means of pipe clamps. To preserve air tightness the dimensioning tolerance, sealing can be applied.

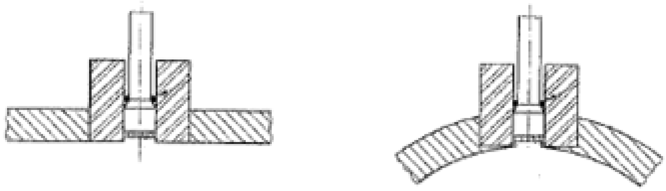


Figure 7. Example of typical microphone mounting [7]

4.4. Microphones principle

Microphone can be divided particular into three groups. Division is proposed based on the response in the sound field. From this group we can distinguish: free field, pressure field and random incidence (also called diffuse field). These types of microphone are based on the same principles. The differences between microphones from group to group are based on frequency response. At the higher frequencies, where the size of the microphones become comparable with the wavelength of the sound being measured. For the purpose of the measurement of the material acoustic impedance the condenser microphone are being discussed.

Condenser microscopes are mainly working using a variable of capacitors. They are working based on the principle of charging metal plate and letting sound move it. The electric field on the plates pushes electrons on the second plate which forms a current. Requirement of the polarization of membrane require a power supply. In most of the cases it is a +200V ´ phantom ´ power.

When a microphone is placed in a sound field it modifies this field. It is of an importance to note how the different microphone compensate its own disturbing presence.

The first group of the microphones is pressure microphone. This microphone measure the actual sound pressure as it exists on the surface of the microphone diaphragm. Construction of the microphones indicates a typical application of microphone. Microphone can be mounted with its diaphragm flush with the surrounding surface, in a closed cavity, at the boundary or wall.

Figure 8**.** Pressure field [10]

Figure 9. Free field [10]

Figure 10. Diffuse field [10]

The next group of microphone is designated to measure the pressure sound as it existed before the device was introduced into the sound field. The device is used mainly in all the application where the sound generally comes from one direction. Consequently the microphone needs to be pointed out in the direction of the noise source. The typical application of this solution is in outdoor measurements and in the places where there are no reflections or reflection is minimized.

For measurements in highly reflecting surroundings, sound will not have a well-defined direction of propagation, but will arrive simultaneously at the microphone from various directions. This situation might produce an inconvenience. The combination of the sound arriving from the front and from behind of microphone may produce a shadowing effect, it means reducing an actual measurement. For this random incidence the microphone should be chosen to respond uniformly to arriving signals. Therefore the statistical consideration was proposed for a measurement technique defining the standard distribution of an arbitrary noise [10].

4.4.1. Characteristic of microphone parameters

- **Polarization of the microphone**

Every Condenser type microphone requires a polarization voltage on the cartridge membrane. This requires a polarization which can be supplied from an external power supply or permanent charging of a thin layer onto the microphone back-plate. The externally polarized preamplifiers must be connected to a power supply module or an analyzer input which can supply the preamplifier with the power as well as 200V polarization. The other type of the microphone use CCP (Constant Current Power). Pre-polarized microphone must be connected to an input stage of CCP supply, which provide a constant current appropriate to demands of a transducer. Most of the Power supply possesses a wide frequency range from 1 Hz to well above 200kHz, which is well above a standard application. In many cases to the power module an A-weighting filter is integrated.

- **Frequency range**

Frequency range of pressure transducer is well defined by the construction parameters. The upper limit of the frequencies is associated with the size of the microphone diameter in comparison to the wavelength of the sound. From the theoretical background the wavelength is inversely proportional. This leads to the assumption that the smaller diameter of the microphone diaphragm the higher frequencies it can measure. On the other hand the limitation of the lower frequencies is associated with a parameter measuring the difference of the internal pressure and the ambient pressure. For the proper utilization of the parameter the microphone possess a ventilation channel, which affects the measurement of the dynamic signal.

- **Dynamic range of amplifier**

Dynamic range of the microphone can be associated with the sensitivity. Where the sensitivity represent the ratio of the analog output voltage value to the input pressure. For the analog microphone dependence is straightforward and it tells how many of the volts the output signal will be for a given Sound Pressure Level. With the increase of the voltage the deflection of the cartridge membrane also increase, up to the point where it stick to the other internal body part of microphone. As a consequence of this frequency response in the upper stage it can be notified high nonlinearity in the measured pressure. This leads to define the upper limit of dynamic range at the level where distortion reaches 10% which mostly occurs at about 6 dB higher. On the other hand the lower limit is indicated by ability of device to measure acoustically- excited signal below the level of the thermal noise, where the voltage output exist at around 5 μV [11].

4.5. Preamplifiers foundations

The output signal from a microphone is very weak and cannot be transferred through the cables. To overcome this obstacle to the end of the microphone or in the close distance the preamplifier should be mounted. Preamplifier does not change the amplitude of the system or characteristic but convert high impedance microphone signal to a low impedance.

From the group of the most commonly used devise two of them found to be the most interesting: so called " traditional" preamplifier ant the others CCP(Constant Current Powered). The difference between this two types stands for different application. Traditional type is commonly used for externally polarized microphone. Traditional preamplifiers require an external power supply which delivers a supply voltage and is normally connected via 7-pin LEMO connectors. Other type of preamplifier maintain a constant power supply on the same wire carrying the signal the more complex 7 core LEMO cable can be replaced by standard BNC cable [10] [12].

4.6. Loudspeaker

Device mounted on the opposite site of a duct in comparison to the test sample holder. The diameter of a membrane coin of loudspeaker should cover the at least two-third of the cross-sectional area of the impedance tube. The next step of mounting loudspeaker is to use an insulating enclosure. The rectangular box with an absorptive material prevent spreading of the airborne noise to the measuring microphone and impedance tube. Addition of an elastic fitting insulation should be made to avoid transmission of structure born excitation from loudspeaker box to impedance tube.

4.7. Signal generator

The requirements that the signal generator has to fulfill are to generate a sinusoidal oscillation. The signal should be stationary with a flat spectral density within frequency range of interest. For the purpose of measurement the signal should have a discrete frequency characteristic and so called sweep generation. The first generated signal correspond to necessary calibration purpose where the second in the great extent is responsible for improving speed of performed test. Discrete frequency generator should possess, at least, this following adjustment parameters: type of generated function, frequency, phase, amplitude, and offset. For the measurement of sweep on the other displayed menu the following parameters should be affordable: START and END frequencies, SWEEP timer to insert measured time interval.

5. Construction of the measurement setup

In this chapter the construction of any measurement apparatus necessary for measuring the acoustic characteristic will be described. Worth to note is that the construction of impedance tube is a further development of the previous student work. The new construction are in most cases elaboration of the error analysis that appear in the previous experimental tests.

For the previous construction some of manufacturing problems were not avoidable, such as not straightness of the pipe induced by welding temperature effects. High ambient noise level introduce a huge error in the proper measurement. The noise itself might be produced by two effects: such as ventilation system of the signal process equipment or the noise produced on BNC connectors of used Measurement Card. We can also refer here to the work of previous student and sensitivity of the microphone. Different level of sensitivity affect in different manner the output signal, which can be clearly visible on spectrogram graph. The region of interest is the frequency range for impedance tube measurement. For the microphone of higher sensitivity the characteristic line can be better visible w.r.t background noise. Undoubted difference can be noticeable on the low sensitivity microphone, where all region of interest is cover by higher intensities of signals. In this case Background noise is situated on intensity of only a few size classes below the signal [13].

Novel apparatus exploits an equipment previously utilized by the acoustic laboratory, and the parts fabricated by DLR workshop and an external supplier. The design of Impedance tube is based on ISO standard 10534-2. The metal construction part where in all developed in construction department based on semi-finished product in stock. Every other signal processing equipment and sensors were delivered by external supplier with provided calibration certificates.

For the new construction set of improvements and recommendations were applied. To some of them belongs: increased frequency range, performing the test in isolated laboratories to prevent spreading of the noise, increased of number of microphone to improve accuracy, preserved high modularity of the system, usage of factory calibrated measurement microphone and other peripheral devices.

5.1. Description of chosen equipment

The most important part of measurement setup is impedance tube itself. The specifics of the layout were mapped on an example of previous student work. For the purpose of simplicity the duct was chosen to be a circular shape. The dimensions of the extreme position flanges were preserved the same to retain possibilities of attaching the same equipment, such as: loudspeaker enclosure, test specimen holders and backing termination plate. Nevertheless, several changes were propose such as: changes of the internal tube diameter, length of the tube, or sealing groove and helium fittings.

The diameter of the tube were selected based on limitation equation to avoid cross-mode that occur at higher frequencies when the acoustical wavelength approaches the sectional dimension of the tube. Thus we decrease the diameter from 80 mm to 51.2 mm. This increase the upper frequency limits from

$$\mathrm{f}_u < 0.586 \cdot \mathrm{c}_0/d = 0.586 \cdot 343 /0.08 = 2460 \text{ Hz} \tag{34}$$

to about

$$\mathrm{f}_u < 0.586 \cdot \mathrm{c}_0/d = 0.586 \cdot 343 / 0.0512 = 3925 \text{ Hz} \tag{35}$$

However this frequency limitation is not satisfactory for a measurement of self-excited instabilities of 1T mode that occur in Combustor BKD at the frequency of 10kHz. To solve this a changes in an acoustic medium were proposed. Medium sufficient for this purpose is Helium. It possess several arguments for using a measure, such as: higher speed of sound, availability, no toxicity. Now the frequency range can be represented by equation below, which serves as significant improvement to study the acoustic behavior at obtained higher modes.

$$\mathrm{f}_u < 0.586 \cdot \mathrm{c}_0/d = 0.586 \cdot 1007 /0.0512 = 11\,525 \text{ Hz} \tag{36}$$

The length of the tube were chosen L=693mm based on recommended distance between speakers and microphone, and also to ensure a spacing distance, s, between two measurement microphone to be at least 2 to 3 inner diameter of tube.

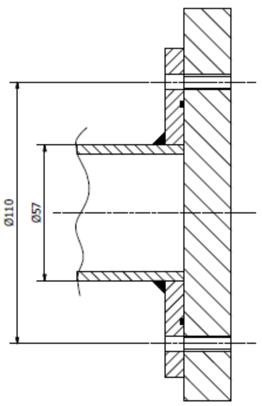
An example of chosen design is presented on the following figure.

Figure 11. Impedance Tube design

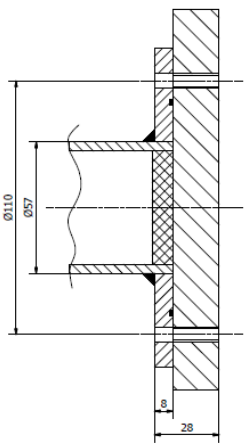
On the one end of impedance tube the loudspeaker is mounted. The loudspeaker of VISATON FR 58 - 8 Ohm were chosen. The dimensions of the following full-range speaker is 5.8 cm (2.3") with coated paper cone. Very linear and wide frequency response and low resonant frequency provide a wide range of applications. The frequency response for a system is within a range of 120- 20 000Hz. The loudspeaker box stay the same as previous student experiment.

On the opposite side of impedance tube the test sample holder can be found. Due to the fact of high modularity of the previous and current construction solution the apparatuses were not changed.

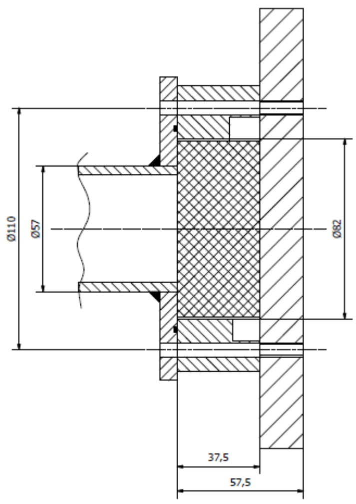
In the process of construction design one of stage of planning was consideration on type of specimens are going to be tested. From this phase several configuration of measured specimen were proposed. An example of nominated structure can be seen below.



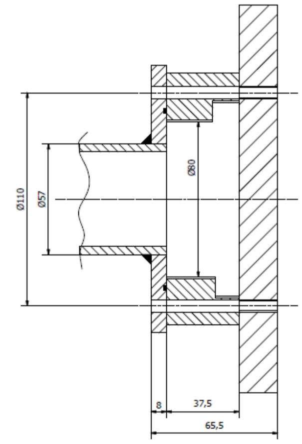
Rigid connection

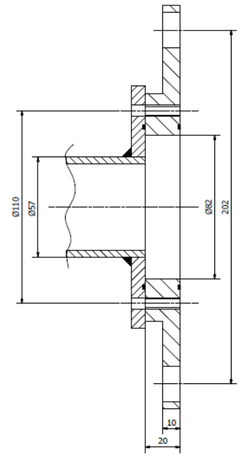


Specimen in a tube



Specimen in a holder





Disassembled injector head | Injector head assembly

Figure 12. Sample holders connections

The construction of the microphone adapter and plugs stays the same as the original version. The base plate with connection plugs are connected to the tube via pipe clamps. After connecting the assembly to tube the provisional check of air tightness should be made. At the place of contact a sealant were propose.

Figure 13. Microphone adapter

Figure 14. Selected Microphone and preamplifier [12]

The most important part of acoustic measurement equipment are microphone with built-in preamplifiers. An extensive study has been made on choice of microphone for a given application. In Chapter 4.4 and 4.5 the fundamental knowledge about this devise is then well defined. For the purpose of impedance tube the sets of microphone were bought, namely G.R.A.S. 46AG- FV 1/2'' LEMO with built-in preamplifier. The new concept of microphone set is an advantage and propose simple, reliable and robust solution. The whole unit is calibrated as one unit, so this eliminates errors because there is only one sensitivity value to account for and the risk of contaminating the interface is eliminated. The microphone cartage is a high-quality externally polarized, free-field, condenser microphone with cartage diameter of ½ (see **Figure 14**). Frequency range(+/- 2dB) of microphone is between 3.15-20kHz , set sensitivity 12 mV/Pa. The microphone set is terminated with a 7-pin LEMO 1B connector and ready to use cable assemblies with LEMO connectors of various types and lengths.

After the proper microphone and preamplifier has been selected, the corresponding cabling, power supplies, signal conditioning and data acquisition system need to be installed. To perform as specified, the G.R.A.S. 46AG microphone set requires a power module or an analyzer input which can supply the preamplifier with power as well as 200 V polarization. For this purpose a power supply of Microtech Gefell MN900; 2 channel were utilize. The input signal is coupled to the output without any filtering or A-weighting network. There is also a polarization voltage switch offering 0 or 200V options for the microphones. Later on this measurement signal via BNC connectors is transmitted to the measurement card coupled with measuring computer. The computer consist of National Instruments PXIe-1071 chassis with BNC 2120 measurement card. To evaluate the signal a LabView SignalExpress 2012 Data Acquisition Assistance were used. For an excitation purpose of a loudspeaker a signal generator FG 200 Yokogawa were used. The following device fulfill every requirements that are put on a signal generator mentioned in section 4.7. The generator is connected to loudspeaker via amplifier system, namely DynaVox Stereo HiFi. Sources generator is also linked to measurement card via TRIG IN/GATE IN connector. This one is provided to initiate wave generation at a specific time. It is convenient to produce a signal at the same time the measurement system is gathering the data. In other words it serves as trigger to signal generator and acquisition system.

The entire structure of Data Acquisition System can be seen below.

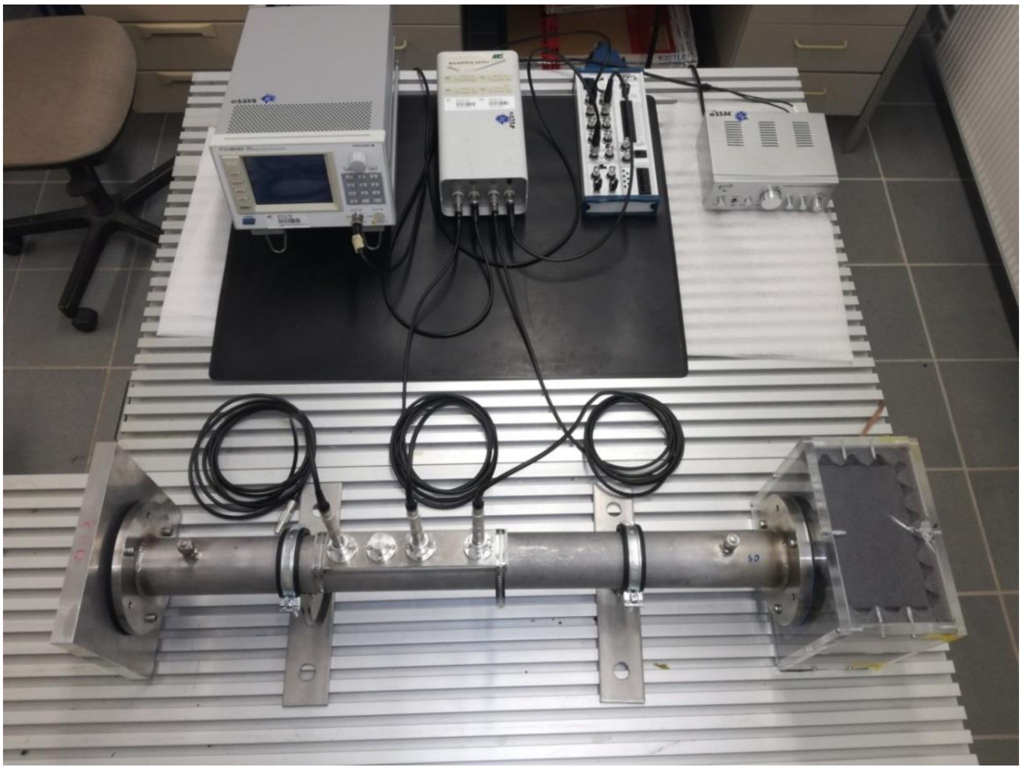


Figure 15. Measurement equipment

6. Measurement procedure

Essential, to accurately measuring the acoustic impedance, is a proper measurement of speed of sound. The importance of the precisely knowing speed of sound is evident when relating the relative acoustic impedance to the boundary acoustic impedance.

The velocity of sound can be assessed acoustically with a knowledge of the tube medium temperature equation.

The equation below are presented for an air and for helium.

$$c_{0,air} = 343.2\sqrt{T/293} \quad c_{0,helium} = 1007\sqrt{T/293} \tag{37}$$

Where

$T -$ is the temperature in Kelvin.

The density of the air, ρ, can be calculated from

$$\rho = \rho_0 \frac{p_a\,T_0}{p_0\,T} \tag{38}$$

Where

$T -$ is the temperature in Kelvin,

$p_a -$ is the atmospheric pressure, in kilo Pascals;

$T_0 = 293K$ $p_0 = 101.325\,kPa$; $\rho_{0air} = 1.205\,\frac{\mathrm{kg}}{\mathrm{m}^3}$; $\rho_{0helium} = 0.1664\,\frac{\mathrm{kg}}{\mathrm{m}^3}$, [14]

Zo – is the boundary specific acoustic impedance for a given medium and is a product of $\rho_0 c_0$.

Initially, the microphones are installed in the specially designed microphone cup. It is necessary to mount microphone cartridge as flush as possible with the round bottom of the adapter. Than this adapter are inserted into Microphone holder and screw to them.

Before the beginning of the acoustic impedance measurement procedure, it is necessary to briefly introduce how the sample are mounted in the impedance tube. The sample is inserted into a sample holder so its reflecting surface is flush with the flange of the holder. This holder are mainly adapters presented in the section 5.1. The sample holder is screwed into the end of the acoustic measurement tube.

The first step in measurement of acoustic properties, after mounting of the test specimen, is the specification of the reference plane. Typically this coincides with the surface of the test specimen. However, if the test specimen has a surface profile, it shell be placed some distance in front of the test specimen.

The selection of an amplitude should be based on comparison of background noise at all frequencies of interest to the selected signal amplitude. Practice proves that amplitude signal should be at least 10dB higher than a noise.

6.1. Improved method for acoustic impedance measurement

Having selected the essential components for the acoustic impedance tube, it is now time to present the procedures used in impedance measurement. As it was mentioned earlier, the following components were used throughout the procedure: the acoustic impedance tube assembly, FG 200 Yokogawa signal generator, DynaVox Stereo signal amplifier system, the measuring computer consisting NI PXIe-1071 chassis with BNC 2120 measurement card. For the preliminary measurement the old microphone were utilized, namely reference mic. MK221 Microtech Gefelle, and measuring microphone MK301/302. This was the case till the new sets of microphone with a better parameters were bought, such as G.R.A.S. 46AG-FV.

The measurement execution can be done in two ways. On one hand, discrete frequencies, on the other, using so-called sweep frequencies. At a sweep mode a signal is going through plurality of frequencies in a certain time interval. At the discrete mode the particular frequencies of interest are chosen. Based on this method only a tabular acoustic coefficient can be obtained. More information reader can found in work of Ruemmler [13], which contains all necessary steps to prepare for set up and end detailed instruction of measurement evaluation.

6.2. Processing the Sample Data using MATLAB

Two separate measurement are needed for a measurement of one sample. The microphone is located initially in one of three possible position and the other two are closed with a plugs. Once a measurement have been made, the microphone is set in another position and the same measurement is carried out. Data acquisition is achieved using the LabView 2012th dynamic signal analyzer. Data acquisition is triggered by the synchronous output of the signal generator FG 200. Triggering is set to coincide with the rising edge of the signal transmitted by the driver. (This is falling edge of the TTL trigger signal). In the block workspace the basic parameters have to be inserted, what makes the further process to handle automatically. In the LabView script the following parameters must be adjusted: sampling frequency, temporal length of measurement and save location of a file.

As mentioned earlier, a MATLAB program were developed to compute the acoustic impedance using improved transfer function technique. A brief illustration of how this programs works is now provided. The program initially request the user to input a file containing the data from microphone position No.1, such as: time signal, voltage signal from reference microphone and voltage signal from measurement position No.1. At the very beginning the signal is stored into the matrices. Later on the raw signal is filtered from the frequencies outside desired measurement range. Than filtered signal is transformed using FFT method. This leads to calculation of complex transfer function. After reading the data for first measurements, the same procedure is conducted on the data from second measurement position No.2. With helps of this two calculated complex transfer function the overall transfer function can be calculated. This serves as a basis to calculate reflection, impedance and absorption [5]. All the results are then plotted in frequency domain.

7. Measurements

First of all an improved transfer function method is evaluated for the different type of materials. Before presenting the experimental results, it is necessary to briefly touch on a tube open and closed end theory and the measurement provided by previous student assignment. This is very important because it provides a theoretical value for an acoustic impedance in which the measurement techniques may be compared. Even though a discrete frequency results can be obtained in the system, these one will not be considered. More plausible results with a continuous absorption curves can be obtained using a sine wave sweep as an excitation signal.

7.1. Previous student work

The first results were compared with a previous student work. The so called materials probe chosen are closed end; open end and foam. Since this measurement use an old design impedance tube with an old microphone sets the frequency range for impedance tube are state base on equations: 31 and 32 to be between 400Hz to 2300Hz.

Set parameters:

Sampling frequency: 25.000Hz
Sampling time: 240s
Used microphone: MK221; MK301/302
Used impedance tube design: OLD

Signal generator:
Mode: Sweep
Start frequency: 2300Hz
Stop frequency: 400 Hz

CLOSE END

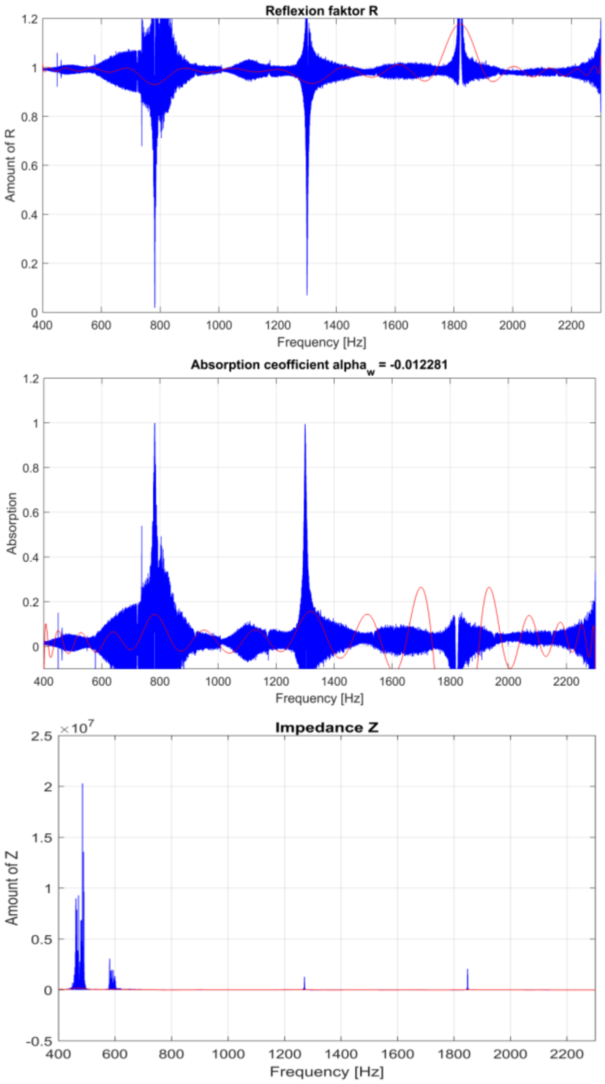


Figure 16. Reflection, absorption, impedance of CLOSE END

OPEN END

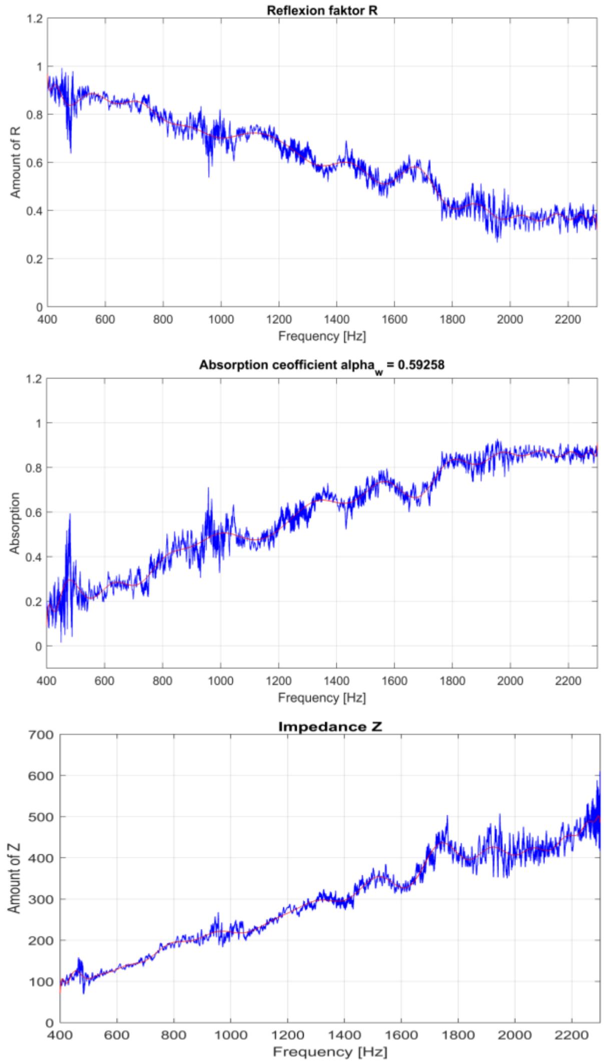


Figure 17. Reflection, absorption, impedance of OPEN END

FOAM

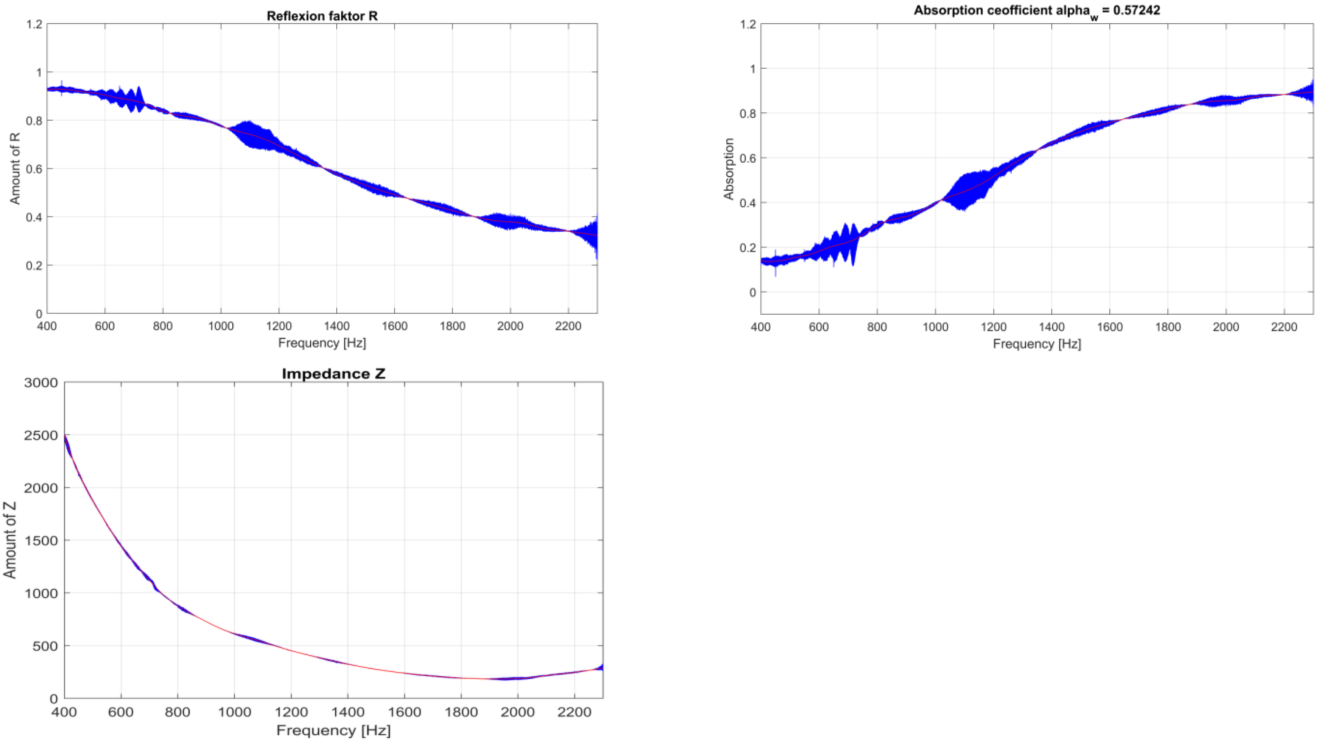


Figure 18. Reflection, absorption, impedance of FOAM

Three different type of material were compared at the preliminary measurements and characteristic parameters were obtained. In the measurement of close end- the fixed termination were used. For the solid ending the final results for reflection coefficient are at the level of 1. This match the theoretical background of sound energy propagated toward rigid formation is reflected without any attenuation. In the measurement with a closed pipe, the peaks of amplitude clearly can be noted. They represent a formation of a standing wave. This phenomenon will be described precisely in the further evaluation. For the measurement with the open end a drop of reflection factor with an increase of frequency can be noted. Again a formation of a standing wave pattern can be clearly recognizable. As an addition of a measurement a piece foam material were performed. The characteristic of a given signal is very smooth comparable to the previous one. The frequencies, where scattering of the signal occur, can be considered to be a point where acoustic resonance frequency or structure-born noise appear.

7.2. Measurement of Advanced Porous Injector materials characteristic

Since the new material was available for a measurement the investigation on the properties were performed. The process of calculation of raw material is crucial for a prospective injector head measurement. This serves as a first step to evaluate essential characteristic for the implementation of the boundary values in simulation of combustion instabilities within rocket combustion chamber. Further steps should contain the measurements of an individual head and then head in combustion chamber. Suitable specimen of sintered bronze and wire mesh were accessible for preliminary measurements.

Set parameters:

Sampling frequency: 25.000Hz
Sampling time: 120s
Used microphone: MK221; MK301/302
Used impedance tube design: OLD

Signal generator:
Mode: Sweep
Start frequency: 2300Hz
Stop frequency: 400 Hz

Sintered bronze

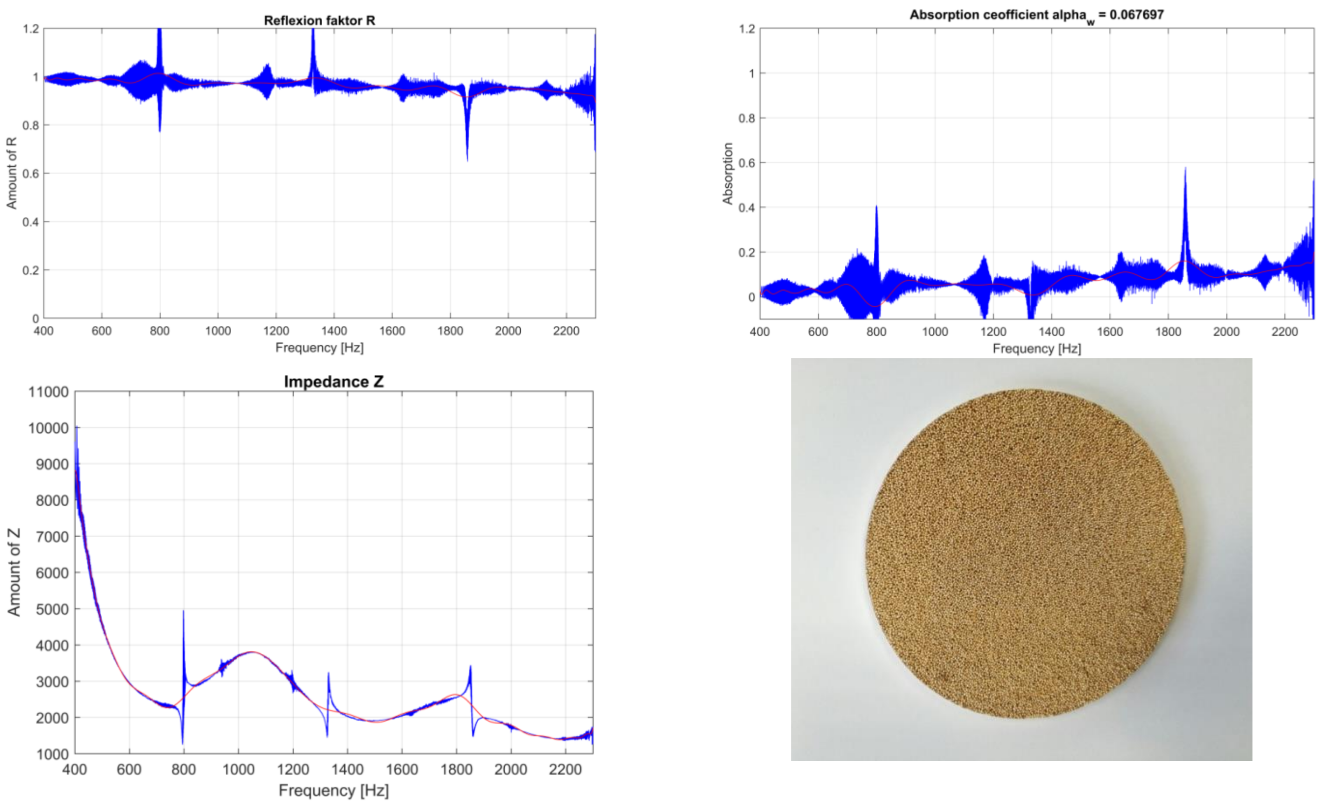
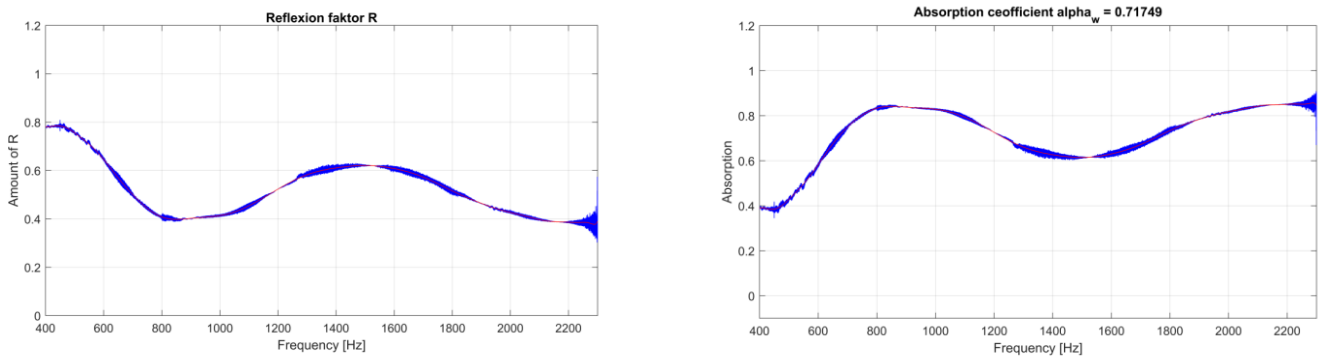
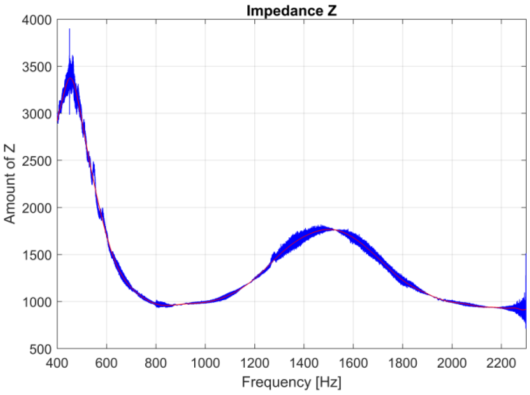


Figure 19. Reflection, absorption, impedance of Sintered Bronze

Wire-mesh





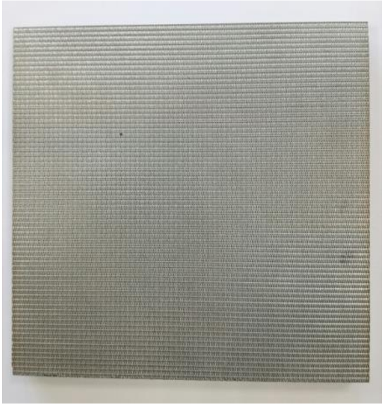


Figure 20. Reflection, absorption, impedance of Wire Mesh Plate

An identification of the parameters for a porous materials can be obtained. From the measurement of sintered bronze the coefficient of reflection and absorption possess similar characteristic as rigid termination. Also from the measurement can be seen the acoustic resonance frequencies of the duct. For the measurement of the wire mesh, specific approach for measured were applied. The size of the sample is different from the conventional one and exceed a dimension of a sample holder. To obtain a parameters a wire mesh plate were attached to the tube flange with helps of a grippers. An rigid back plate as well as rubber sealing were also used. Rubber sealing in this measurements served as air- tightening enclosure. Measured reflection and absorption vary with a frequency change. It is very clear from the graph representation why the measurement of acoustic parameters are essential, the fact is that it is hard to predict a component response in a different frequencies.

7.3. Longitudinal standing wave

This chapter presents a simplified model of sound propagation in a duct, for purpose of prediction of longitudinal standing waves. Modelling the propagation of sound in a duct is a classic problem and under a common low-frequency assumptions, the sound waves propagating in a rigid tube are planar, or an one dimensional in nature.

A loudspeaker is mounted at the disturbance end of the duct acting as a source of noise. It is a common approach in the literature [15] to impose the boundary condition of a closed end here. In this case, the loudspeaker is considered to be a volume velocity source. This approach does not include the interaction between the loudspeaker and the duct. A system model which assumes a pure pressure or volume velocity source neglects this coupling. A full electromechanical model of the loudspeaker should be coupled to the duct model to properly represent the disturbance end.

A simple notion is that the fundamental resonance of a pipe occurs when the sound wavelength is half or a quarter of the resonator length.

Lets now look at the case where a pipe is closed on both ends. From the theory, at the end of closed ending the node is formed to let the standing wave to exist. The figure below shows standing wave in a pipe and pressure variation associated with this.

Pressure variation

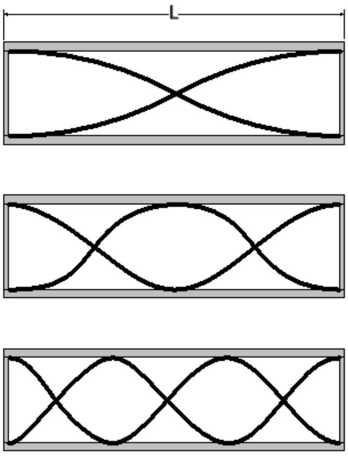


Figure 21. Closed- Closed

λ	f
$\lambda_1 = 2 \cdot L$	$f_1 = c_0/2\,L$
$\lambda_2 = L$	$f_2 = c_0/L$
$\lambda_3 = 2/3 \cdot L$	$f_3 = 3\,c_0/2\,L$

$f_1\,;\;\; 2f_1\,;\;\; 3f_1$

1st 2nd 3rd allowable frequencies

The oscillation frequency for the length mode of a half wave tube (a tube with two open or two closed ends) can be predicted as:

$$f_n = \frac{\mathrm{n}\ \mathrm{c}_0}{2\,L} \tag{39}$$

With f_n (Hz) as the frequency, c_0 (m/s) as the speed of the sound, L (m) as the tube length and n as the mode number.

Now look at the case where one end is closed one is opened. The pressure variation for the first allowable frequencies are presented at the Figure 22.

Pressure variation

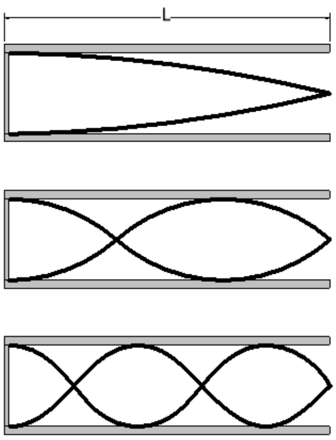


Figure 22. Closed- Open

λ	f
$\lambda_0 = 4 \cdot L$	$f_o = c_0/4\,L$
$\lambda_1 = \frac{4}{3}\,L$	$f_1 = 3\,c_0/4\,L$
$\lambda_2 = \frac{4}{5} L$	$f_2 = 5\,c_0/4\;L$

$f_0\,;\;\; 3f_0\,;\;\; 5f_0$

1st 3rd 5th allowable frequencies

The frequency of the resonance in axial direction in a quarter wave tube (a tube with one open and one closed end) is

$$f_n = \frac{(2n - 1)\, c_0}{4\, L} \tag{40}$$

The proposed theory serves as an indication of the frequencies where standing waves forming in the tube can be detected. Formation of this patterns is strictly correlated to the acoustic resonance frequencies of the tube and the position where a high amplitude peak will be visible.

7.3.1. Experimental verification

The theory need also be proven with an experimental verification. For the first test, newly design tube were utilized. The two boundaries condition were tested, namely open end and closed rigid termination. As a noise signal a white noise were chosen due to the fact it contains all frequencies in equal proportion. The measured signal are obtained from reference microphone and microphone from the position No.1.

Set parameters:

Sampling frequency: 25.000Hz
Sampling time: 30s
Used microphone: MK221; MK301/302
Used impedance tube design: NEW

Signal generator:
Mode: White Noise

CLOSED- OPEN CLOSED- CLOSED

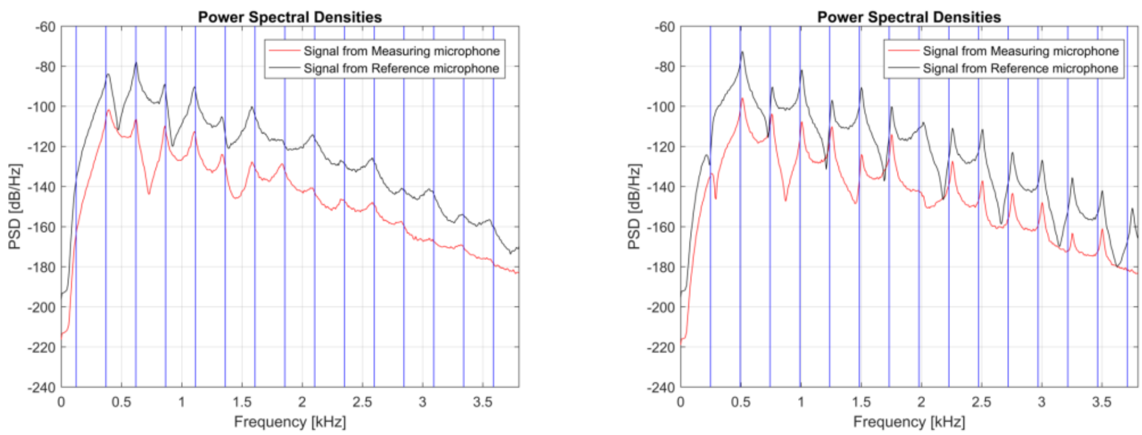


Figure 23. PSD of white noise signal from tube: closed- open and closed-closed

As can be seen from the Figure 23, the agreement of the theoretical value and measured is very good. On both graphs red and black curve represent a Power Spectral Densities of a signal from microphones. Blue vertical lines present a theoretical value obtained from equation 39. And 40.

A theoretical and fully experimental solution for a longitudinal wave propagation were also analyzed for a newly design tube filled with a helium. New medium increase a capabilities of a design for a frequencies range measurement. According to equation 36. we can increase a frequency range till 11.525Hz. Performed measurement are consistent with a methodology presented in the previous section.

Set parameters:

Sampling frequency: 25.000Hz
Sampling time: 30s
Used microphone: MK221; MK301/302
Used impedance tube design: NEW

Signal generator:
Mode: Sweep
Start frequency: 3800Hz
Stop frequency: 400 Hz

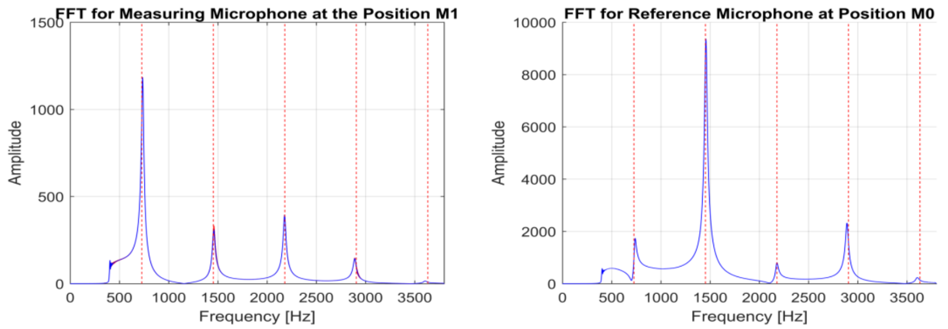


Figure 24. FFT analysis of a raw signal from microphone at the position M1 and M0

The theoretical model is very accurate up to about 3500 Hz. Figure 24 illustrate the FFT response in a frequency domain. In all figures, it can be seen that the model agrees very well with the theory.

For a better understanding of further experiments the loudspeaker electromechanical model might be coupled to the duct system model at the disturbance end, providing a better fit to experimental data than more simple boundary condition. This model might serves as extension to the three dimensional problem, permitting the study for more complicated applications.

7.4. Measurement with Helium

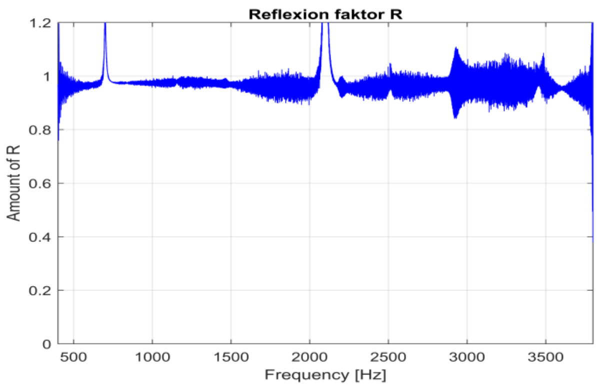
In order to investigate higher frequencies by means of Increasing frequency range we need to fill a tube with a medium possessing higher sound velocity, namely helium. Due to much higher speed of sound characterizing the upper limit the frequency range can be increased. Performed measurement were consistent with a methodology presented in the Measuring procedure section. The list of set parameters are shown below. To obtain acoustic parameters the tube were tightly closed. Two sets of Swagelok connection allows to insert a helium straight from the bottle. The additional procedure for filling the impedance tube also require a security measure in case of hazardous situation. After filling in the tube the pressure inside the apparatus need to be stable at the level of 1 bar. For this value the gas parameters are known. At the moment where stable condition were obtained the normal measurement procedure were performed.

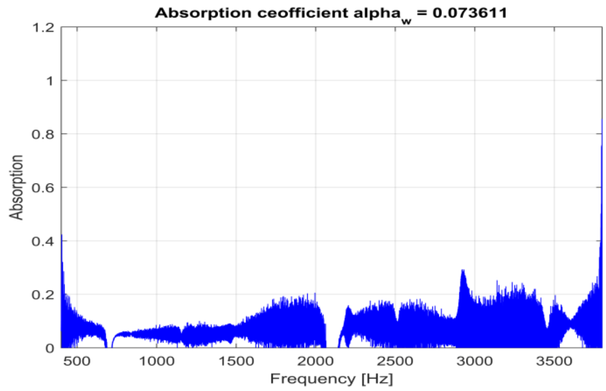
Set parameters:

Sampling frequency: 25.000Hz
Sampling time: 60s
Used microphone: MK221; MK301/302
Used impedance tube design: NEW

Signal generator:
Mode: Sweep
Start frequency: 3800Hz
Stop frequency: 400 Hz

New Design, Old Microphone, filled with Helium Closed End, $f\_range=400–3800Hz$, Amp: 5Vpp,





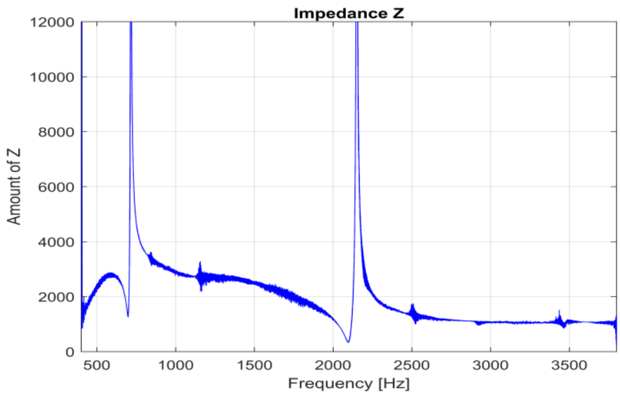


Figure 25. Reflection, absorption, impedance of CLOSED END

As previously discussed, an applied boundary condition are close ending on both site. The figure above illustrate all three most common material acoustic characteristic. In all figures, it can be seen that the model agrees very well with a data in the region till 3800Hz. And the unpredictable disturbance do not appear in the system. Good experimental agreement over the frequency range 400-3800Hz permits a robust design of a impedance tube up to 11kHz. However, small peaks which still are noticeable into the systems can be filtered. For the following a new microphone with a calibrated response can be used.

7.5. New design

After noting highly encouraging results from the previous sample test, a new design with a calibrated microphone were exploited. Once again, the procedure documented in the previous chapter were followed to obtain the acoustic impedance measurements. For this assessment three different type of material were tested, namely: foam, open end- and advanced porous material- sintered bronze. In all of this cases the specific, for a different purpose ,sample adapters need to be used. At this test new microphone were used, however as a main sound medium were used air not helium. In a further test, if the helium wanted to be used, the sealing of the microphone adapter need to be improved. At this particular phase, this type of connection was not working.

Again the two microphone transient measurement are plotted together to enable comparison.

Set parameters:

Sampling frequency: 25.000Hz
Sampling time: 120s
Used microphone: 46AG- FV 1/2''
Used impedance tube design: NEW

Signal generator:
Mode: Sweep
Start frequency: 3800Hz
Stop frequency: 400 Hz

New Design, New Microphone, Without Helium Foam, $\boldsymbol{f\_range}=\mathbf{400-3800}\boldsymbol{Hz}$, Amp: 2Vpp,

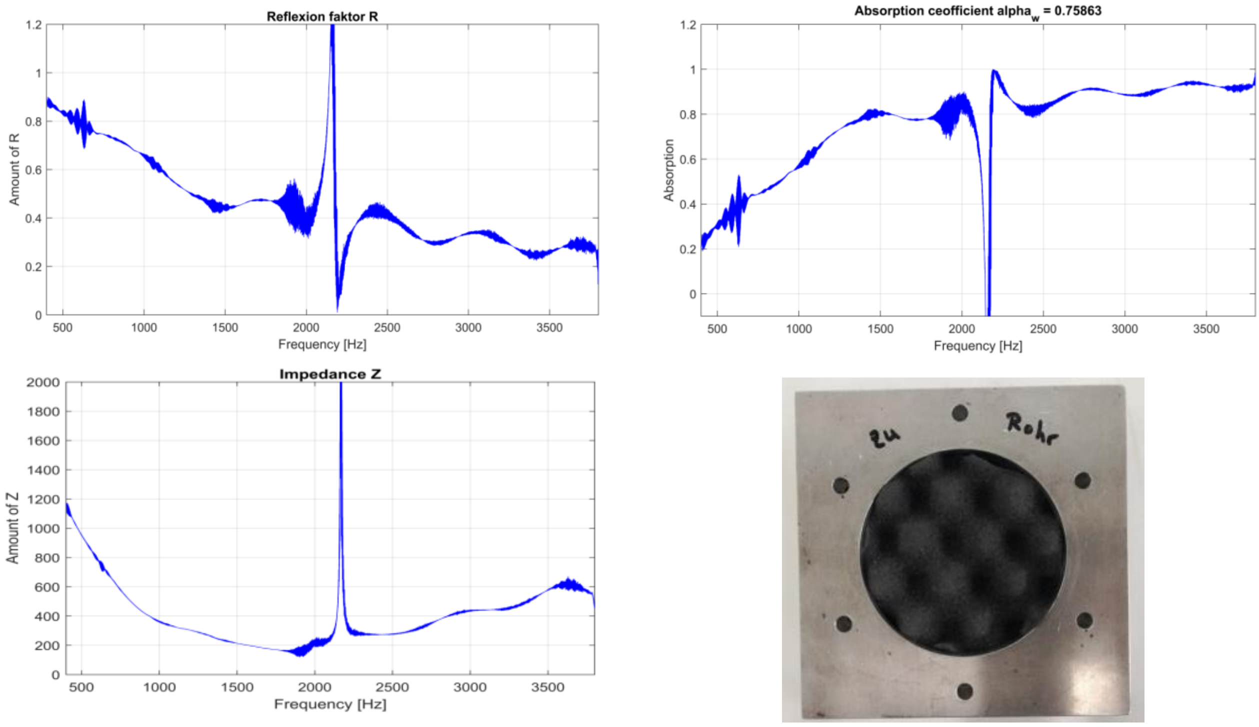


Figure 26. Reflection, absorption, impedance of FOAM

New Design, New Microphone; Open, $\boldsymbol{f\_range}=\mathbf{400-3800}\boldsymbol{Hz}$, Amp: 3Vpp,

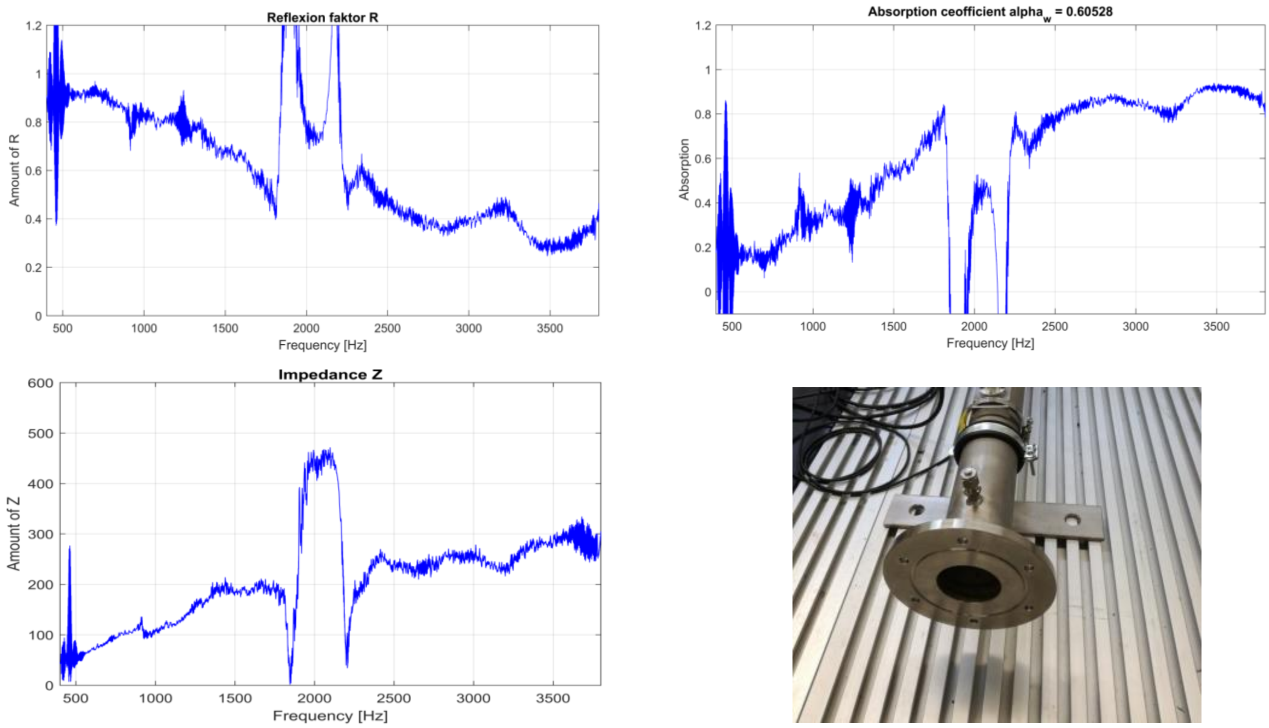


Figure 27. Reflection, absorption, impedance of OPEN END

New Design, New Microphone; Sintered bronze, f_range=$400–3800Hz$, Amp: 2Vpp,

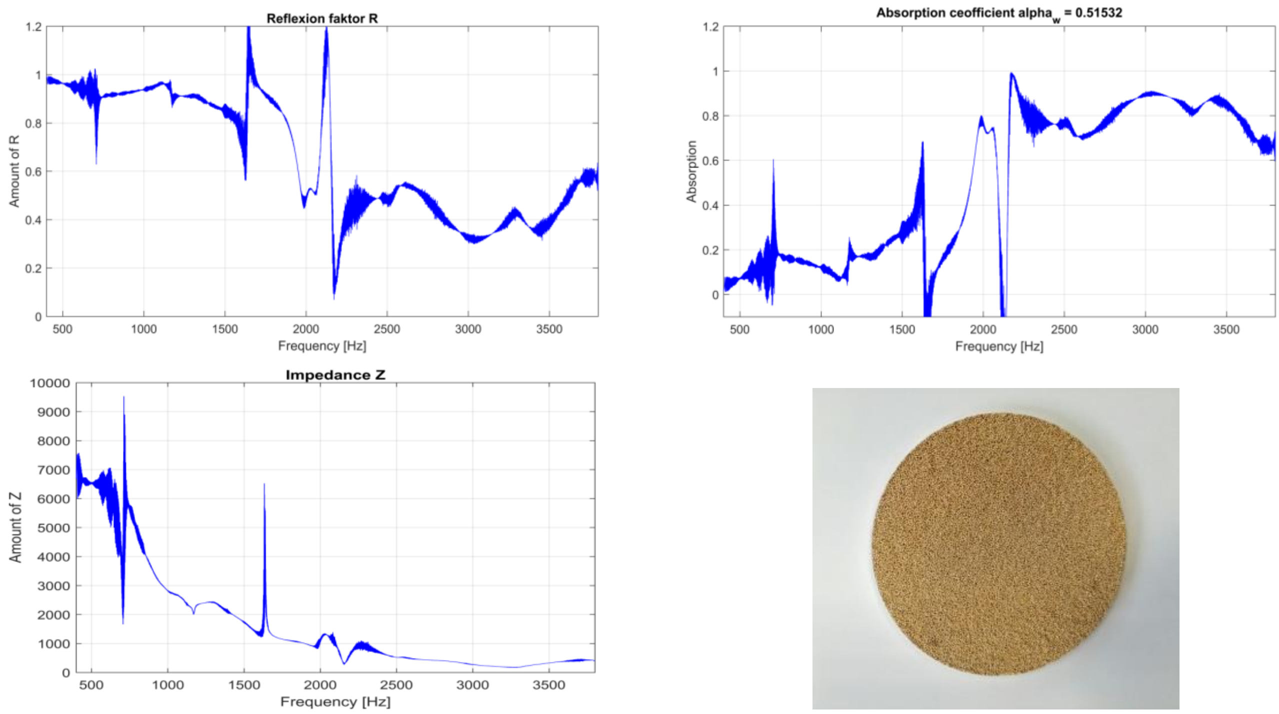


Figure 28. Reflection, absorption, impedance of Sintered Bronze

Since all of the measurement are similar to the previous tests, the trends exhibited during impedance measurements are similar as well. This method exhibits slightly more oscillation at frequencies near frequencies 1600 and 2100Hz.

Novel measurement method, generally is more favorable comparison to the old method. This is very encouraging because the transfer function method can be performed much more rapidly over a wider range of frequencies.

8. Summary

8.1. Conclusion

The aim of this assignment was to develop an acoustic measurement tube with an improved working frequency range. The methodology employs set of fixed microphones that can be used quickly to measure the acoustic impedance of any material placed in the sample holder at the end of the tube, over a frequency band of 0.4 to 11.5 kHz. A new laboratory experiment was developed using this impedance tube.

First a brief Literature review was made of the different methods used in acoustic impedance measurement. Using basic definitions and theory, principal equations were developed for analysis using two microphones. MATLAB programs were developed that use those equations to compute the acoustic impedances from the raw laboratory data.

Next, several components were investigated for the acoustic impedance tube: the microphone, amplifier, power supply assembly, DAQ and the loudspeaker. Area worth exploring is the use of a higher quality microphone. Linearity is the most important quality of a microphone used in this apparatus; sensitivity is not an issue. The use of a higher quality microphone, without doubts, yield better results. Also the new mechanical design of impedance tube were evaluated based on principal assumption. This one are affordable in Attachment section.

Having developed the apparatus and theory, it was necessary to establish a test procedure and provide a means for measuring the acoustic impedance of a sample material. A laboratory handout was prepared, to enable students to conduct acoustic impedance measurements using this apparatus.

The final step was to validate the effectiveness of this acoustic impedance measurement tube and its developed techniques. This was successfully accomplished by making "open tube", “closed tube” and “previous student assignment work” measurements and comparing the results to established theory over the frequency range of 0.4 to 2.3 kHz. The measurements made using the two-microphone technique are in good agreement with the theory.

Additional measurement were made using sintered bronze and wire mesh, since the calculation are crucial in the process of elaborating prospective API head. Sweep measurements compared to discrete sinusoidal frequencies method gives parameter coefficient curves rather than single values. On the other hand, the constructed tube show a certain drops, when using sweeps as the broadband excitation signal. The drop can be associated with a formation of longitudinal standing wave pattern in a tube. Nevertheless, this effect is less pronounced if using factory-calibrated microphone or using white noise as the excitation signal, rather than sine sweeps technique.

Some improvements on previous work were proposed. By changing an acoustic medium and decreasing tube diameter the affordable frequency range can be increased from 2.3kHz to an 11.525kHz. As a result, acoustical impedance can be measured accurately providing characteristic for implementation a Boundary condition in simulation of Combustion instabilities within rocket combustion chamber.

8.2. Recommendations

Although the acoustic impedance measurement tube was successfully developed, along with a useful procedure and software, there are still some modifications that can further improve the performance of this apparatus. One is the development of a filter that would improve the acoustic impedance measurement results at the low end of the frequency band. Subsequently, when the helium is used the sealing surface between tube and microphone adapter plate need to be checked and restored.

For higher efficiency, every prepared test report should contain a set of information about performed test. High quality preparation of the report has a high influence on processing of the data or in emergency situation allow to repeat the test with a relatively short time with no expected measurements errors. The report should contain most of the following information. A description of the sample adequate to identify another sample of the same material. A description of the test specimen including their number, size and method of mounting. Apart from this information the description should contain an acoustically relevant information such as: flatness of the surface or characteristic profile height, arrangement and thickness layers as well as positions of the cuts of the test sample relative to characteristic line of test objects with lateral structures. A description of instruments used and the details of procedure also should be considered as a part of report. The designated reference plane must be identified clearly.

Bibliography

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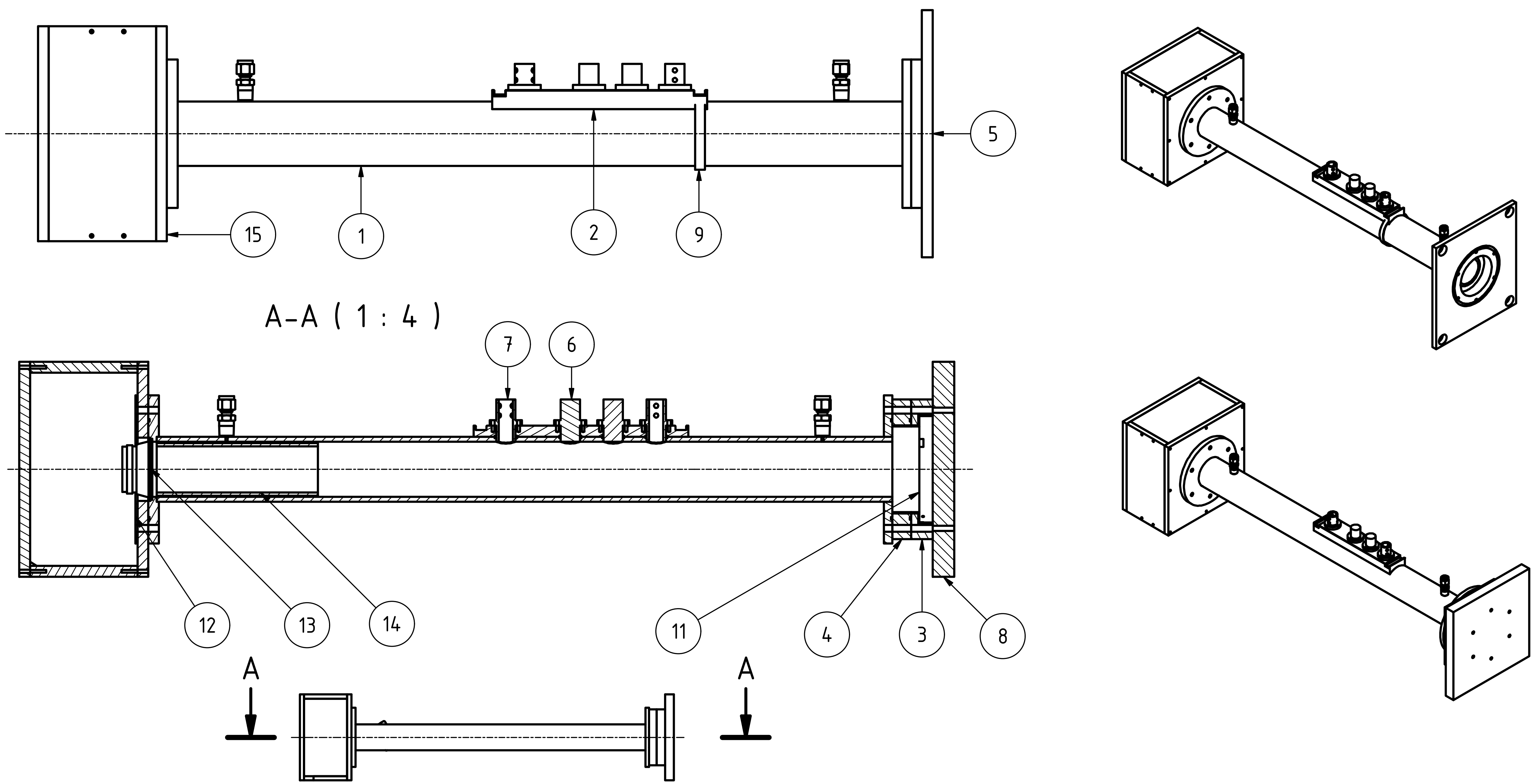
Picture Directory

Attachment

A Design drawings

B Microphone Set specifications



Stückliste

Zeichnungs-/Bauteilnummer	Bauteil
1	Haupttubus
2	Mikrofonhalterung
3	Einzelmessadapter
4	Einzelmessadapterv2
5	Gesamtmessadapter
6	Stöpsel
7	Mikroadapter_groß
8	Fester_Abschluss
9	Schlauchschelle
10	Deckel_LSpKasten
11	Injektorkopf
12	Verspannplatte
13	Lautsprecher
14	Hülse

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5'	±5'

Rauheitsangaben nach DIN ISO 1302

roh	unbeh	a Rz100	b Rz25	c Rz6,3

Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

Material:

Maßstab: 1:5

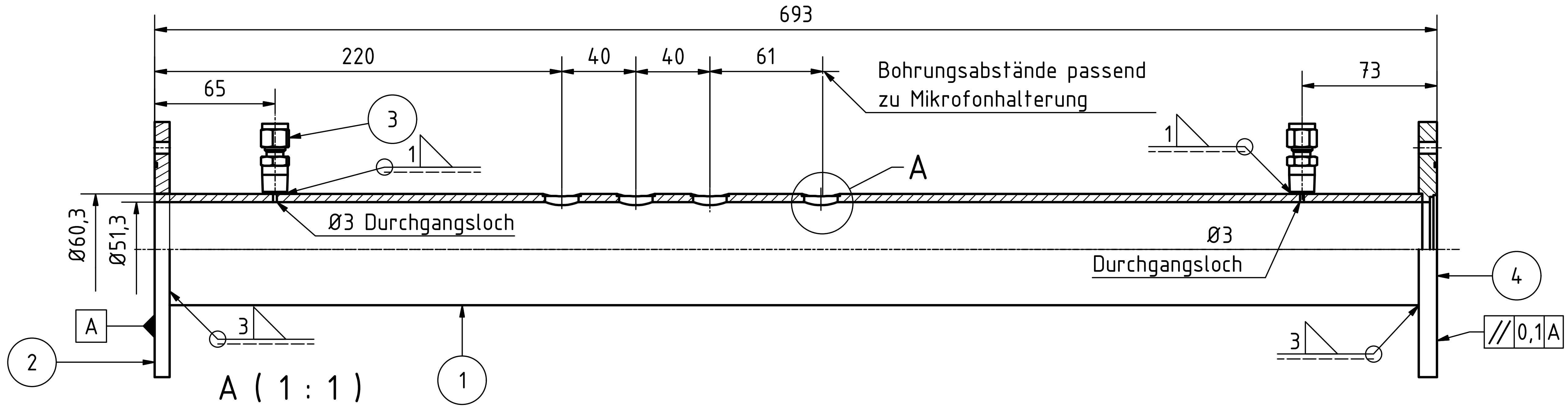
	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

Status	Änderungen	Datum	Name

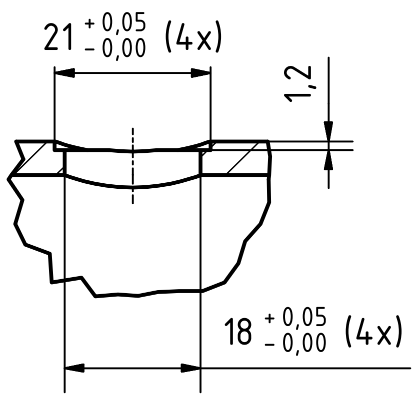
Impedanzrohr - 000

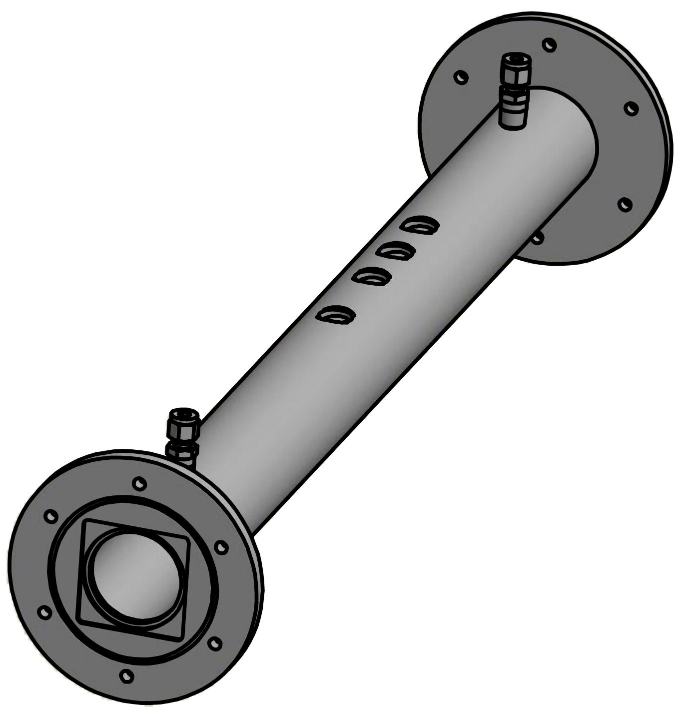
Zusammenbauzeichnung_A1

A3



A (1 : 1)





Teileliste			
ITEM	QTY	PART NUMBER	BEZEICHNUNG
1	1	Haupttubus_V4 L= 685 mm	
2	1	Flansch	
3	2	SS-6M0-1-4-SwagelokCompany	
4	1	Loutsprecherflansch	

Deutsches Zentrum
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Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

Material: 1.4571 + 1.4301

Maßstab: 1:2

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

Impedanzrohr - 001

Haupttubus_A

1

A3

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5'	±5'

Rauhheitsangaben nach DIN ISO 1302

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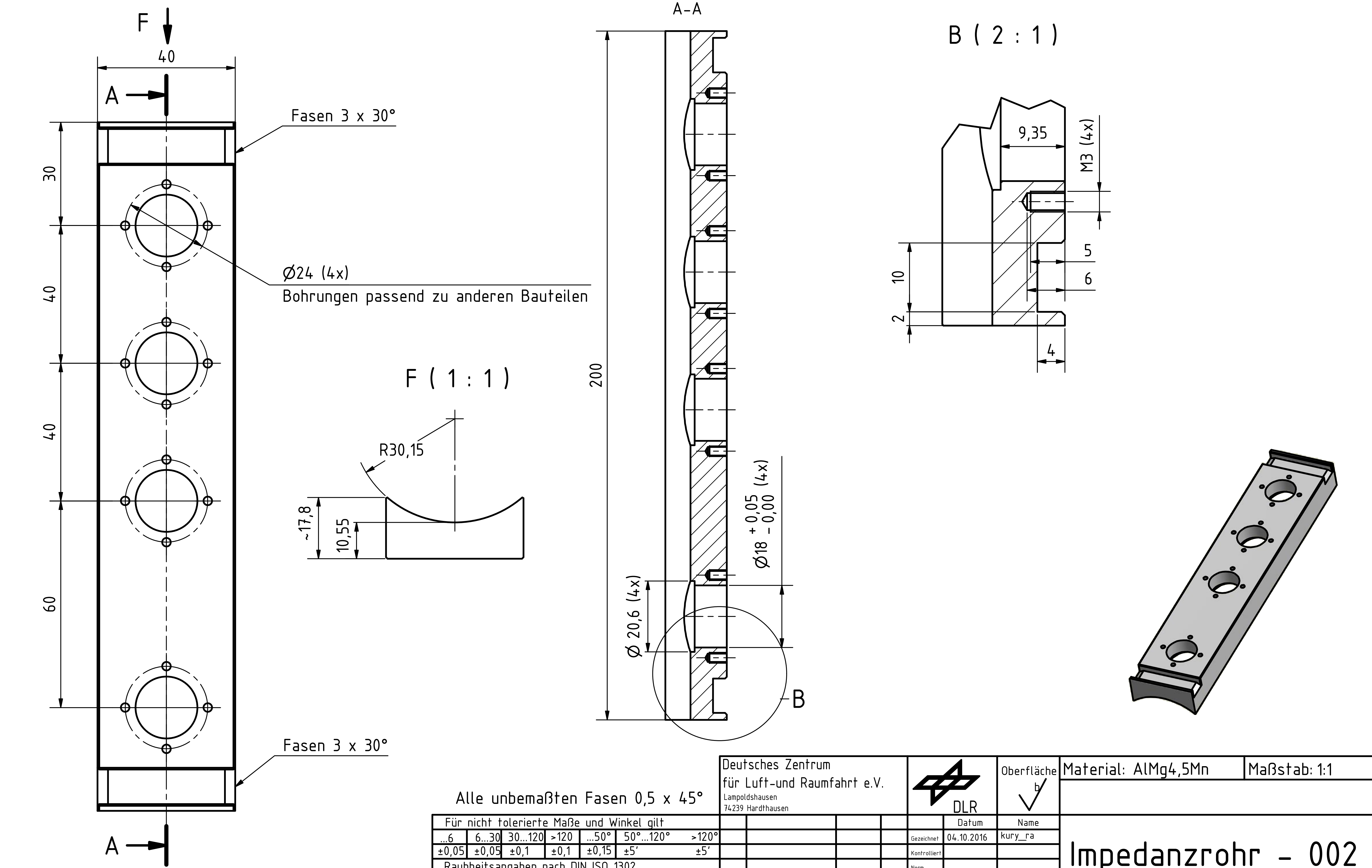
roh	unbeh	Rz100	Rz25	Rz6,3

Status	Änderungen	Datum	Name



Alle unbemaßten Fasen 0,5 x 45°

Für nicht tolerierte Maße und Winkel gilt						
...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5'	±5'

Rauhheitsangaben nach DIN ISO 1302

	a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

Status	Änderungen	Datum	Name

Material: AlMg4,5Mn

Maßstab: 1:1

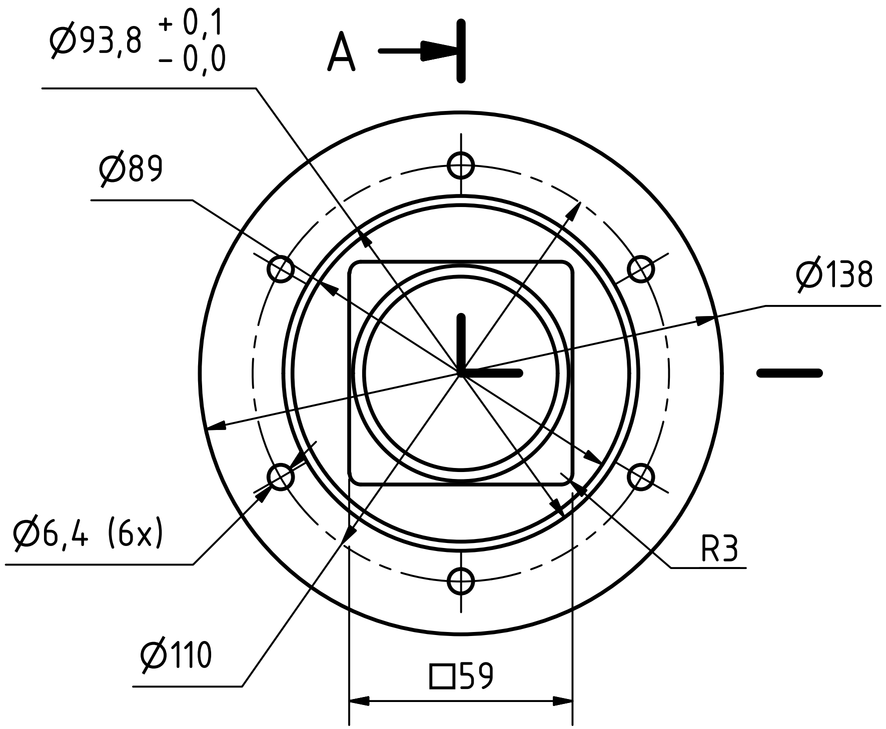
Impedanzrohr - 002

Mikrofonhalterung_A

1

A3

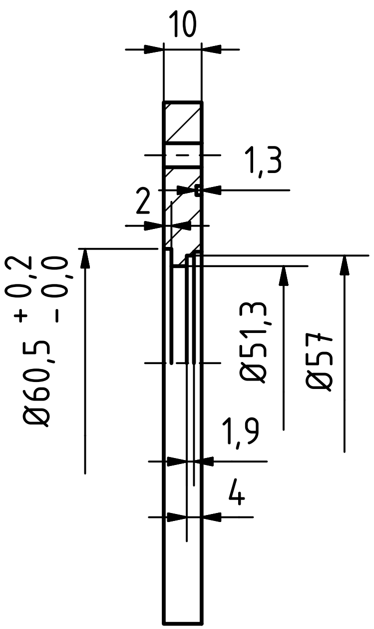
ELEMENT 4: Lautsprecherflansche

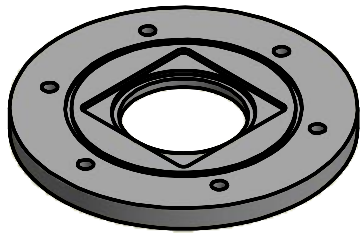


A-A (1 : 2)

vordrehen 11 mm

rechte Seite nach dem Schweißen drehen:
-O -Ring Nut





Deutsches Zentrum für Luft-und Raumfahrt e.V. Lampoldshausen 74239 Hardthausen	DLR	Oberfläche b	Material: 1.4541	Maßstab: 1:1

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5′	±5′

Rauhheitsangaben nach DIN ISO 1302

		a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

Status	Änderungen	Datum	Name

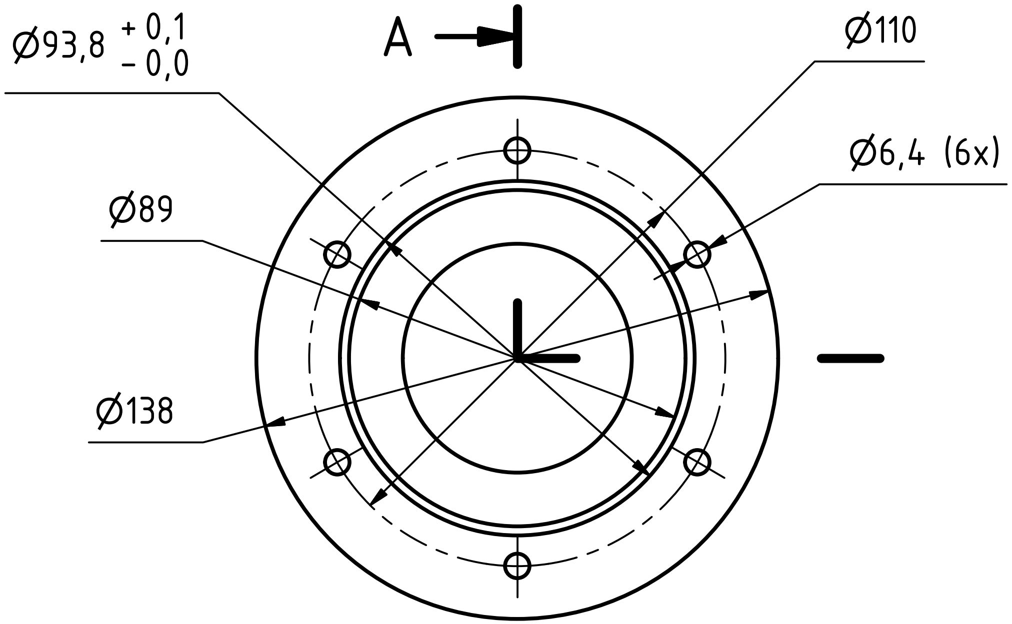
Impedanzrohr - 001

Lautsprecherflansche_A

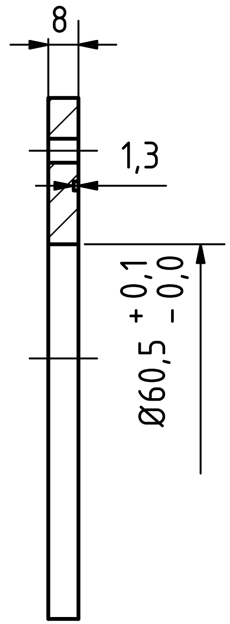
1

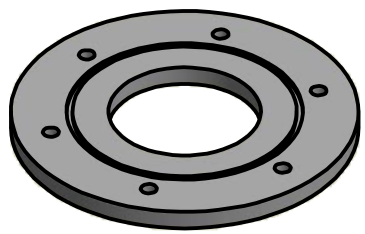
A4

ELEMENT 2: Flansche



A–A (1 : 2)





Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche

Material: 1.4541

Maßstab: 1:1

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5′	±5′

Rauhheitsangaben nach DIN ISO 1302

a b c

roh unbeh Rz100 Rz25 Rz6,3

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

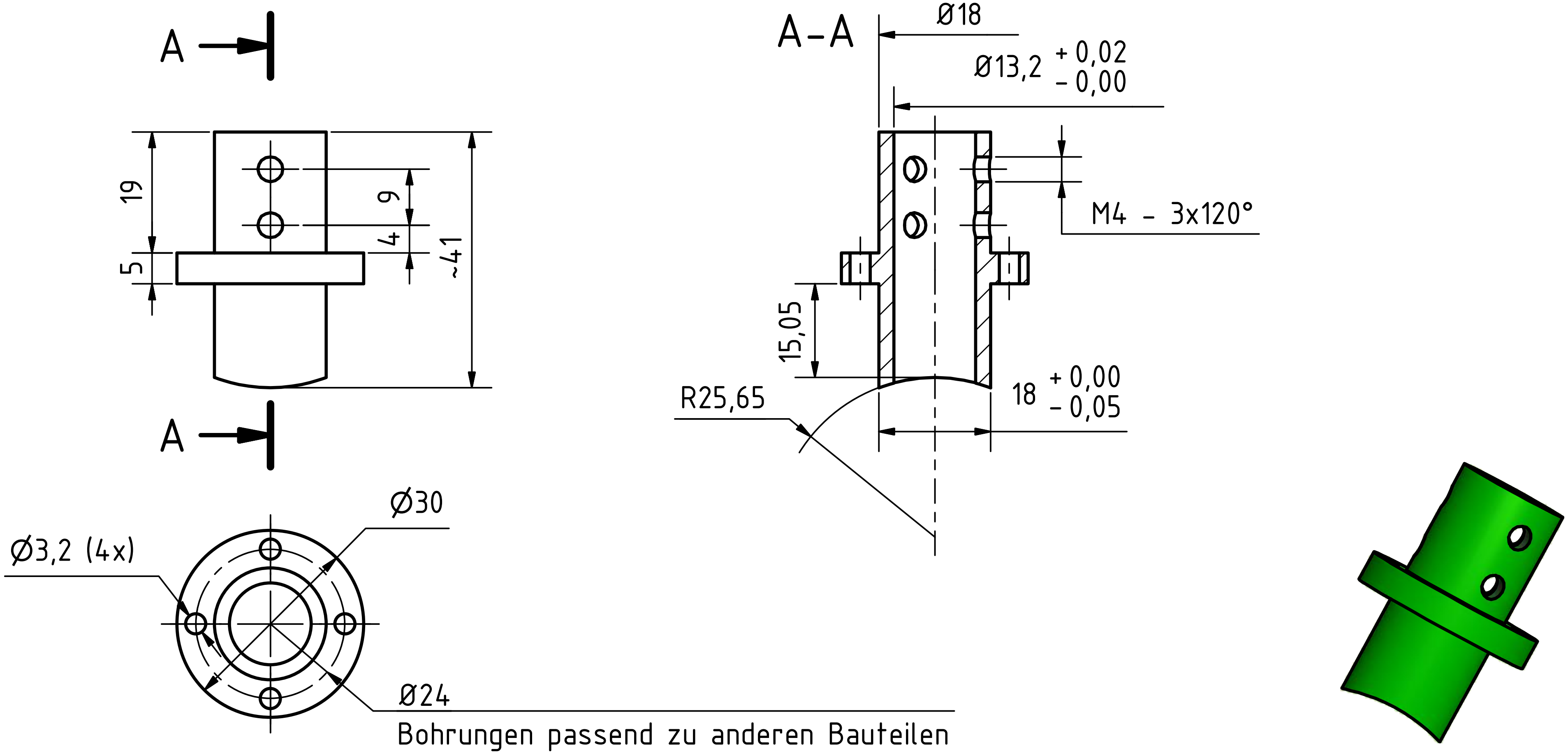
Status	Änderungen	Datum	Name

Impedanzrohr – 001

Flansche_A

1

A4



Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

Material: AlMg3

Maßstab: 1:1

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5'	±5'

Rauhheitsangaben nach DIN ISO 1302

		a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

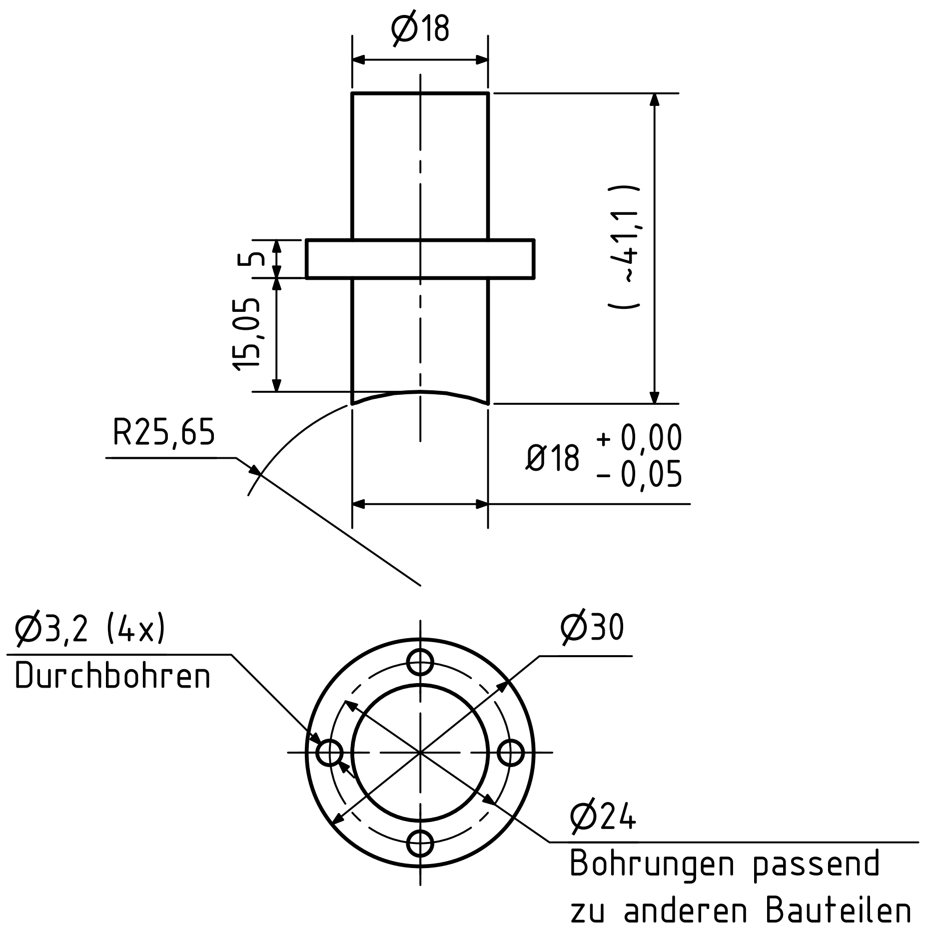
Status	Änderungen	Datum	Name

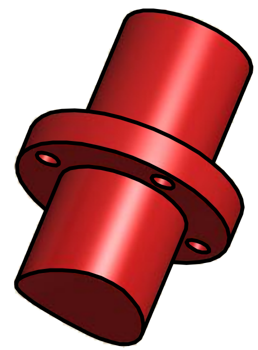
Impedanzrohr - 007

Mikroadapter_groß_A

1

A4





Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

Material: AlMg3

Maßstab: 1:1

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5'	±5'

Rauhheitsangaben nach DIN ISO 1302

		a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

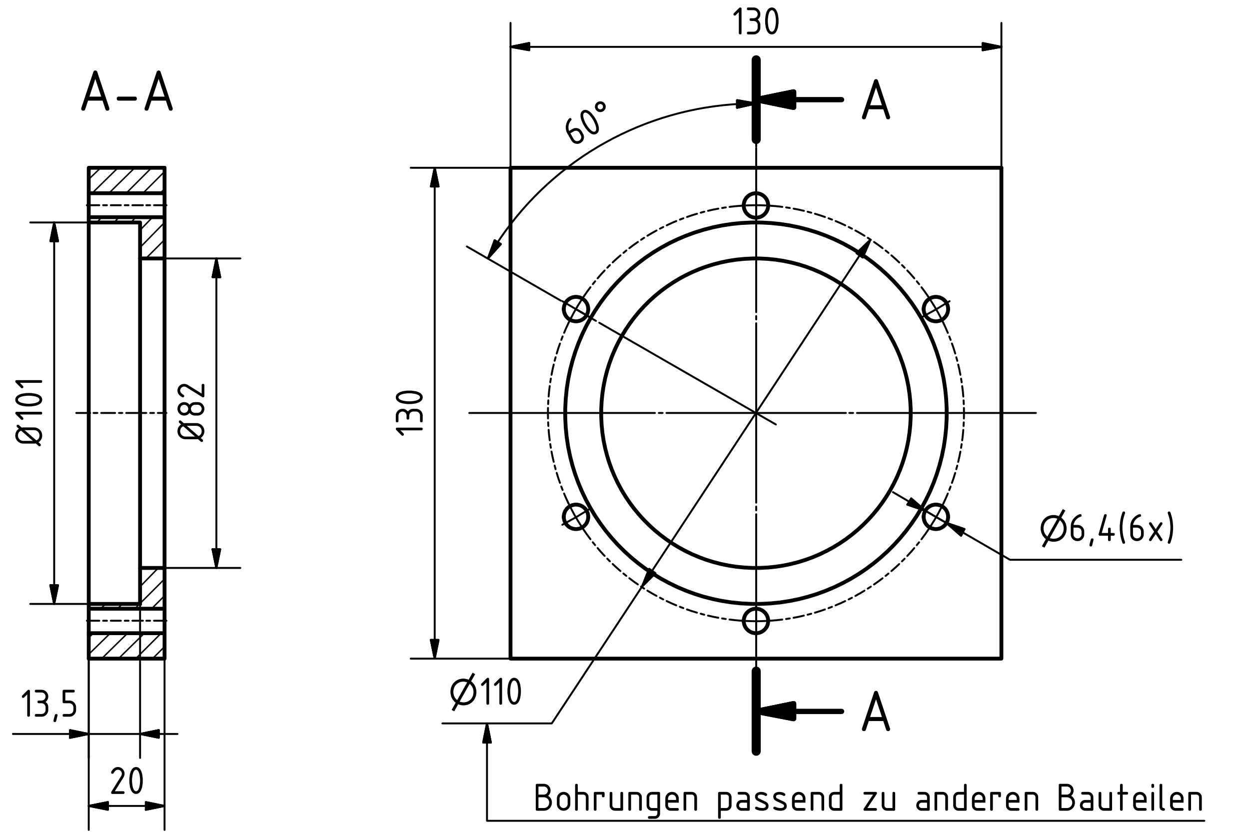
Status	Änderungen	Datum	Name

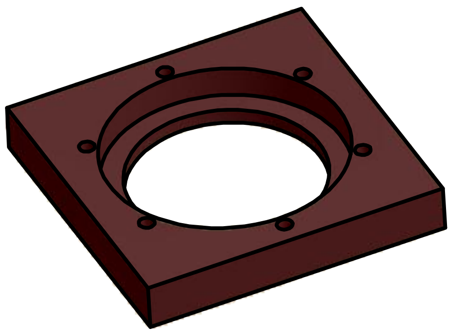
Impedanzrohr - 006

Stöpsel_A

1

A4





Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

Material: AlMg4,5Mn

Maßstab: 1:2

Für nicht tolerierte Maße und Winkel gilt

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±0,05	±0,05	±0,1	±0,1	±0,15	±5′	±5′

Rauhheitsangaben nach DIN ISO 1302

		a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

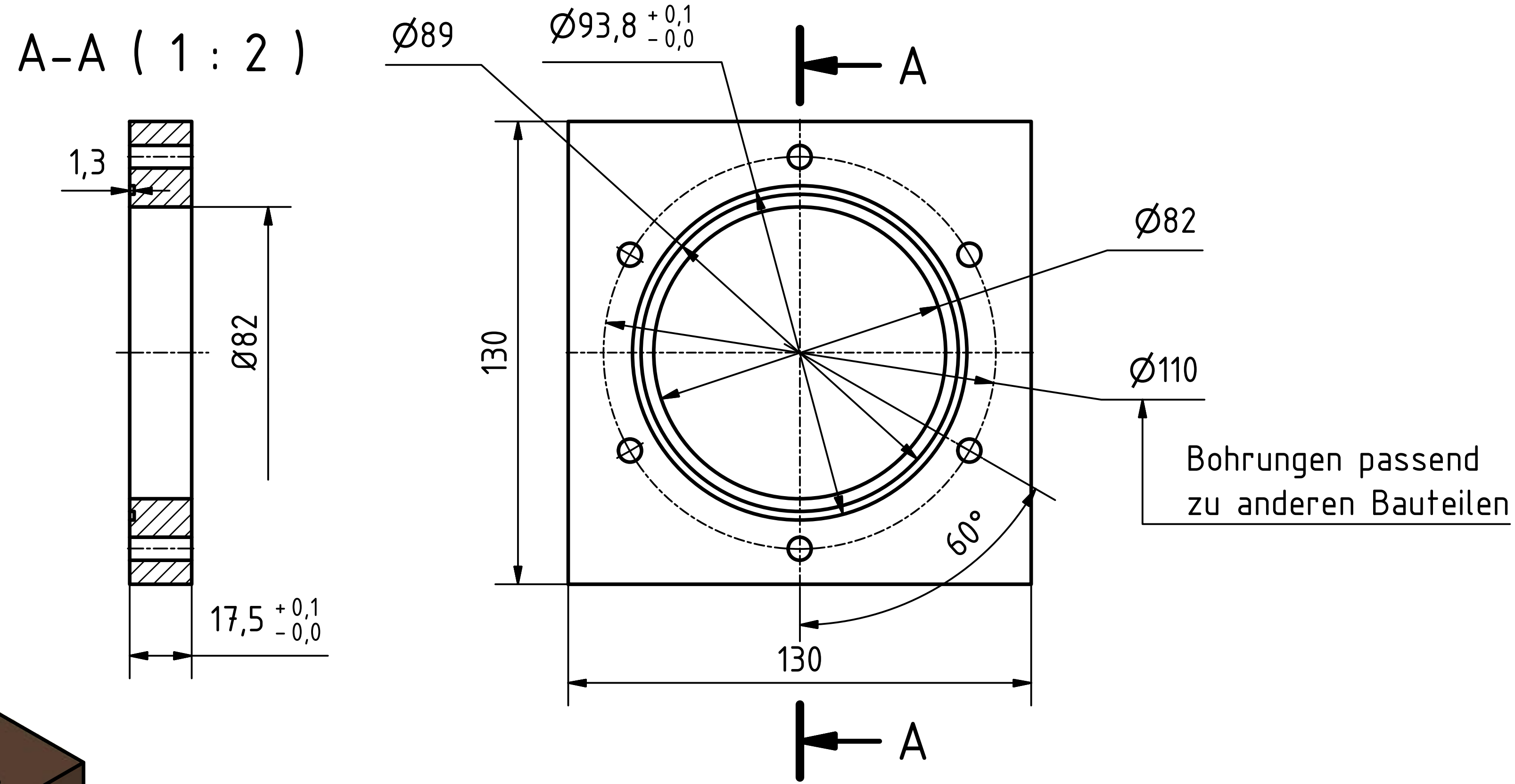
Status	Änderungen	Datum	Name

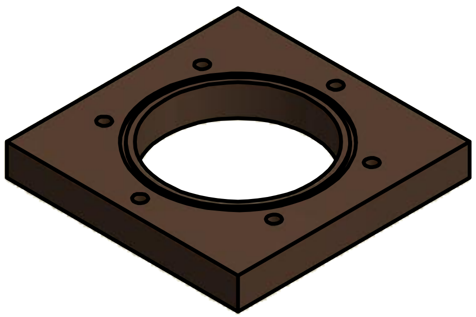
Impedanzrohr - 003

Einzelmessadapter_A

1

A4





Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche b

Material: AlMg4,5Mn

Maßstab: 1:2

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5′	±5′

Rauhheitsangaben nach DIN ISO 1302

		a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

	Datum	Name
Gezeichnet	04.10.2016	kury_ra
Kontrolliert		
Norm		

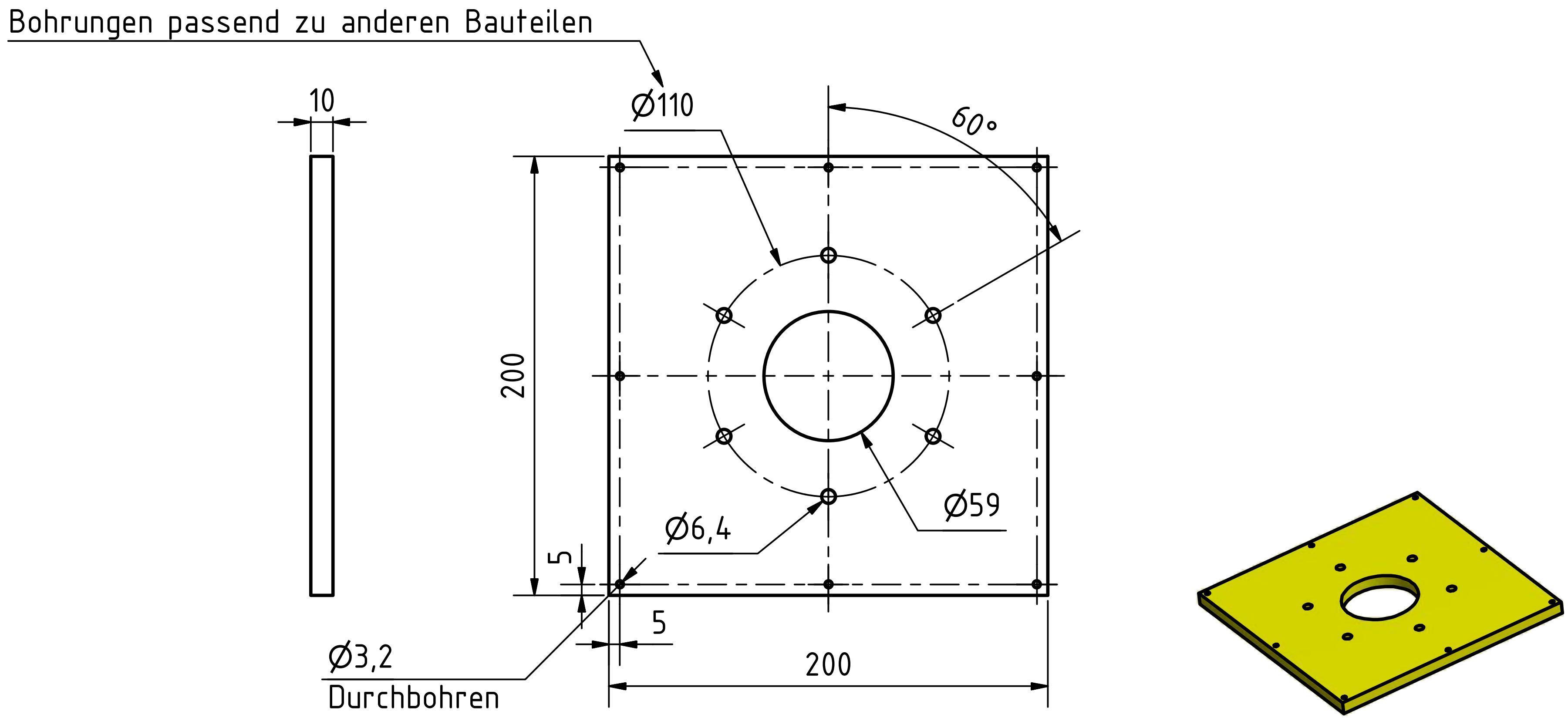
Status	Änderungen	Datum	Name

Impedanzrohr – 004

Einzelmessadapter_A

1

A4



Deutsches Zentrum
für Luft-und Raumfahrt e.V.
Lampoldshausen
74239 Hardthausen

DLR

Oberfläche

Material: Plexiglas

Maßstab: 1:3

Für nicht tolerierte Maße und Winkel gilt

...6	6...30	30...120	>120	...50°	50°...120°	>120°
±0,05	±0,05	±0,1	±0,1	±0,15	±5′	±5′

Rauhheitsangaben nach DIN ISO 1302

		a	b	c
roh	unbeh	Rz100	Rz25	Rz6,3

	Datum	Name
Gezeichnet	05.10.2016	kury_ra
Kontrolliert		
Norm		

Status	Änderungen	Datum	Name

Impedanzrohr - 010

Deckel_LSpKasten_A

1

A4

G.R.A.S. 46AG 1/2" LEMO Pressure Standard Microphone Set

Freq range: 3.15 Hz to 20 kHz
Dyn range: 25 dB(A) to 164 dB
Sensitivity: 12 mV/Pa

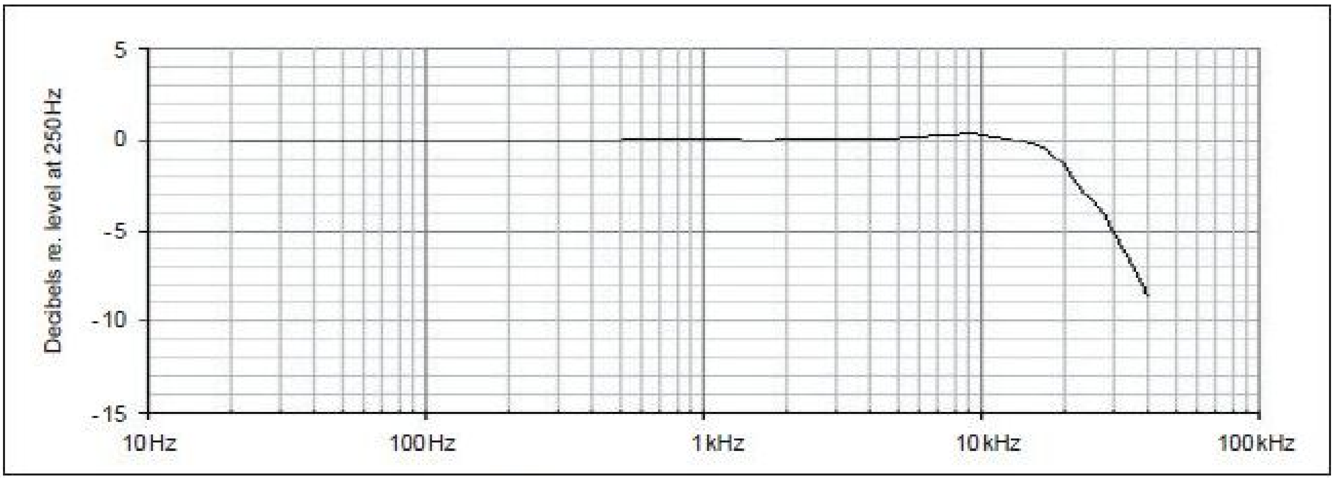
The 46AG is a 1/2" LEMO microphone set for pressure measurements.

Specifications

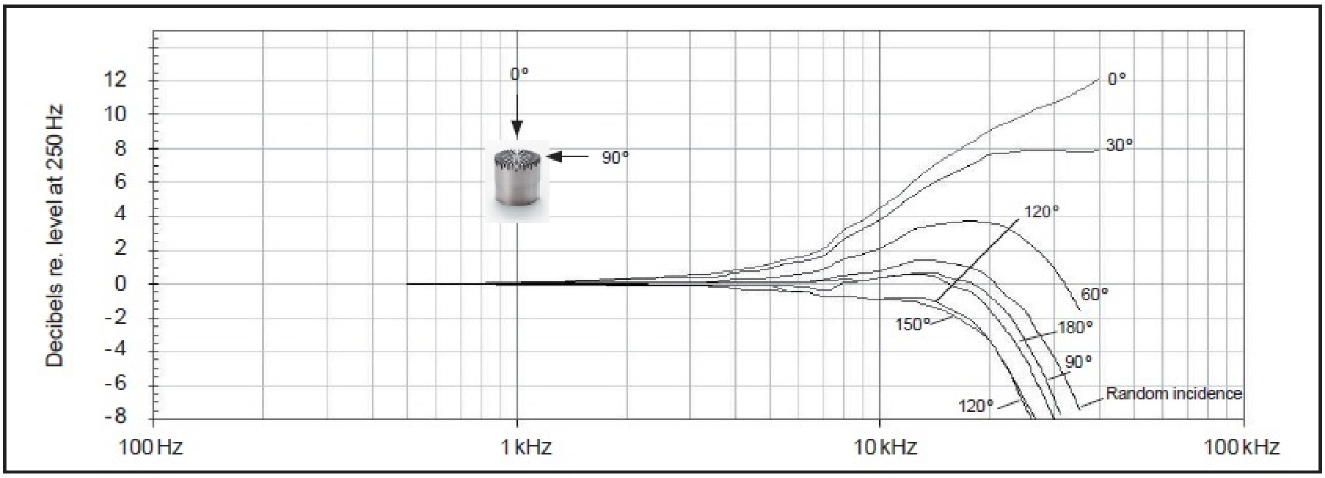
Frequency range (±1 dB)	Hz	5 to 12.5 k
Frequency range (±2 dB)	Hz	3.15 to 20 k
Dynamic range lower limit with G.R.A.S. preamplifier	dB(A)	25
Dynamic range upper limit with G.R.A.S. preamplifier @ +28 V / ±14 V power supply	dB	153
Dynamic range upper limit with G.R.A.S. preamplifier @ +120 V / ±60 V power supply	dB	164
Set sensitivity @ 250 Hz (±2 dB)	mV/Pa	12
Set sensitivity @ 250 Hz (±2 dB)	dB re 1V/Pa	-38.5
Output impedance	Ω	75
Power supply min. to max. (single/balanced)	V	28 to 120 / ± 14 to ± 60

G.R.A.S.
SOUND & VIBRATION

DC-offset, min., single suppy	V	0.5 x Vs - 1
DC-offset, max., single suppy	V	0.5 x Vs + 4
DC-offset, balanced supply	V	-1 to 4
Microphone venting		Rear (Front on request)
IEC 61094-4 Compliance		WS2P
Temperature range, operation	°C / °F	-30 to 70 / -22 to 158
Temperature range, storage	°C / °F	-40 to 85 / -40 to 185
Temperature coefficient @250 Hz	dB/°C / dB/°F	-0.01 / -0.006
Static pressure coefficient @250 Hz	dB/kPa	-0.011
Humidity range non condensing	% RH	0 to 100
Humidity coefficient @250 Hz	dB/% RH	-0.001
Influence of axial vibration @1 m/s²	dB re 20 µPa	66
TEDS UTID (IEEE 1451.4)		27 v. 1.0
Connector type		7-pin LEMO (FGG.1B.307)
CE/RoHS compliant/WEEE registered		Yes / Yes/Yes
Weight	g / oz	33 / 1.164



Typical frequency response.



Free-field corrections for different angles of incidence

G.R.A.S. Sound & Vibration reserves the right to change specifications without notice.

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