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Drinking Straws as a Broadband Sound Absorber

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ABSTRACT

The range of products developed by the most common absorption principles that fulfil high performance tuned to specific frequencies, low price, sustainability and aesthetic quality is often limited to porous materials. The quarter wavelength tube principle may perform well, even in low frequencies, but in a narrow frequency range. To widen the range, multiple tubes can be tuned to multiple frequencies by choosing combinations of lengths and diameters. If designed properly, less material is needed thus lower price and tubes can be easily re-used. Based on a research through design method a more broadband sound absorber using drinking straws has been developed. Measurements of the normal incidence sound absorption coefficient were performed in an impedance tube and compared to an analytical model based on the theory of viscothermal wave propagation in prismatic tubes. Different tube materials and geometries were examined regarding the influence on their performance. The outcomes of this study led to a sound absorber based on 19 different straw lengths that absorbs well in the frequency range from 400Hz till 1000Hz. The importance of these absorbers can be high when it comes to selective frequency performance that needs to be cost- effective, sustainable and aesthetically pleasing.

Keywords: quarter-wavelength tube, sound absorber, drinking straws

1. INTRODUCTION

The sound field in a space is highly influenced by the size of the room and the finishing materials used on the surfaces. For working environments, it is noise which is the most prevalent source of annoyance [1] [2]. Especially regarding open-plan layouts, even though they provide efficiency in terms of spatial configuration [3] and improve the communication between employees [3], speech noise is widely recognized to be disruptive [3]. Open plan spaces often lack in sound absorption and shielding, resulting in big, uncomfortable and noisy spaces. This implies that preventing sound propagation over long distances is important. The main acoustic source of disturbance in an open-plan area is usually speech. Decreasing sound levels in a room usually means the use of a sound absorbing acoustic product. However, a lot of products usually have a fixed performance for a specific frequency range, have no possibility of tuning them to specific frequencies, and sometimes permanently fixed thus is hard to re-use the same products in another space. Last but not least, very few acoustic products have a high aesthetic quality.

By choosing a sound-absorbing principle based on the shape of the absorber and tuning at specific frequencies for high performance offers freedom not only for the acoustic treatment of different spaces but also for the design of the product. The main objective of this research is to develop a design for a free-standing sound absorbing product based on the quarter-wavelength tube principle. Specifically, the design focuses on the production of a series of units that aim at frequencies between 400Hz – 1000 Hz, taking into consideration that the frequency range that is dominating in the A-weighted speech level is 500-100Hz [4]. This frequency range is selected by considering the range of the human voice but because higher frequencies can easily be treated with porous absorbers.

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2. METHODOLOGY

2.1 Theory

The development of the absorber design bases on the results of research, more specifically a comparison between theory and measurements. The working principle of sound absorption in tube resonators is based on the resonance of the air inside the tube. The tubes have an open and an open or closed end and usually have a uniform shape along their length. In the tubes with both open ends and length=L, the energy of a standing wave with wavelength (λ) =2L is attenuated at the node at L/2. For the tubes with a closed end, a sound wave entering one of these tubes will travel to the closed end and be reflected back to the other side where it arrives opposite in phase to the oncoming wave in the pipe. This interference between the two waves determines where peaks in attenuation appear; friction along the pipe walls creates viscothermal damping. Tube resonators are also called half or quarter-wavelength resonators, since the maximum absorption takes place when a half (2open ends) or quarter (1 open, 1 closed end), and odd multiples, of the acoustic wavelength are equal to the resonator's length. The optimal tube length *(L_{eff})* for a quarter wavelength tube can be determined easily from Eq. (1).

$$f_{res} = \frac{2n-1}{4L_{eff}}\,\mathrm{c} \tag{1}$$

Where,
f_{res} is the resonance frequency [Hz], n is any integer starting from 1 and c is the speed of sound in air [m/s]

As mentioned before, the resonator's length determines the main frequencies at which sound is absorbed, and the resonator radius and the ratio of hole/surface of the panel determine the height and the width of the absorption peaks. Due to inlet effects the effective length of the resonator is larger than the actual length. Therefore an end correction is added to the geometrical length of the tube. This effect has been studied extensively for different configurations of the entrance of the tube. The end correction depends on the local geometry at the entrance and ending of the tube. The effective length L_{eff} is the geometrical length L increased by a small increment d [5]. The increment d for a single tube with the opening in an infinite baffle is equal to:

$$d = \frac{8R}{3\pi} \tag{2}$$

Where,
R is the radius of the tube [m]

If the tube is open on both sides, the end correction is applied on both sides [6]. For a perforated panel that is equally distributed by a distance α [m] the end correction for each side is:

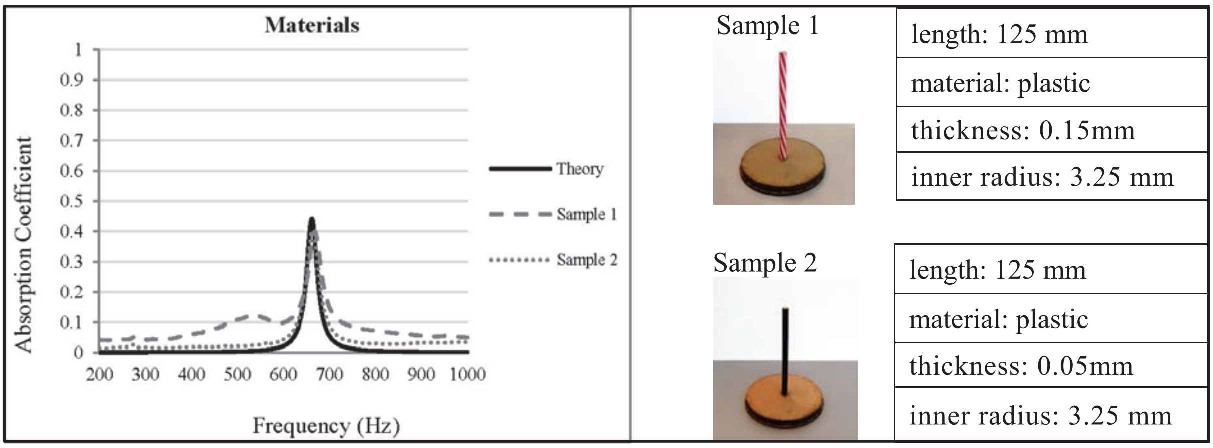
$$d = \frac{8R}{3\pi}(1-0.44\frac{R}{a}) \tag{3}$$

This means that $L_{eff}=L+d$, so according to whether we deal with a single tube or a perforated panel, a different d (eq.2 or eq.3) is taken into account.

This research contains two different steps. First, the theory of quarter wavelength tubes attenuation is translated into a Matlab script based on the theory of viscothermal wave propagation in prismatic tubes [7]. This script is then used to calculate how different tubes and combinations of tubes can be combined to create a certain desired absorption spectrum. At the same time, measurements on samples including different quarter wavelength tubes were conducted in an impedance tube B&K 4206 at the Faculty of Architecture and the Built Environment of the TU Delft, according to EN ISO 11654 [8], tube diameter 10cm; and the outcomes are used for the design development. The impedance tube is chosen because of the controlled conditions it provides and the need of small samples that are easy to manufacture. On the other hand the results are not representative of the performance of a bigger sample and are based only on normal incidence sound absorption.

2.2 Results

The simulations/tests are organized in terms of different tube materials and geometries. The basic materials used are drinking straws. Since here quarter wavelength tubes are investigated, one end had to be capped. The other (open) end was placed in a 1cm thick MDF cylinder to be able to seal the surface airtight around it. The aim is to have results as close to theory as possible and use the outcomes for the design decisions. Below a selection of the results are shown.
The thickness of the plastic material of the tube doesn't seem to influence the absorption performance of the drinking straw, as shown in Figure 1. Small differences of 6 Hz-7 Hz might be resulting from the 1-2 mm of length difference of the two.



Sample 1

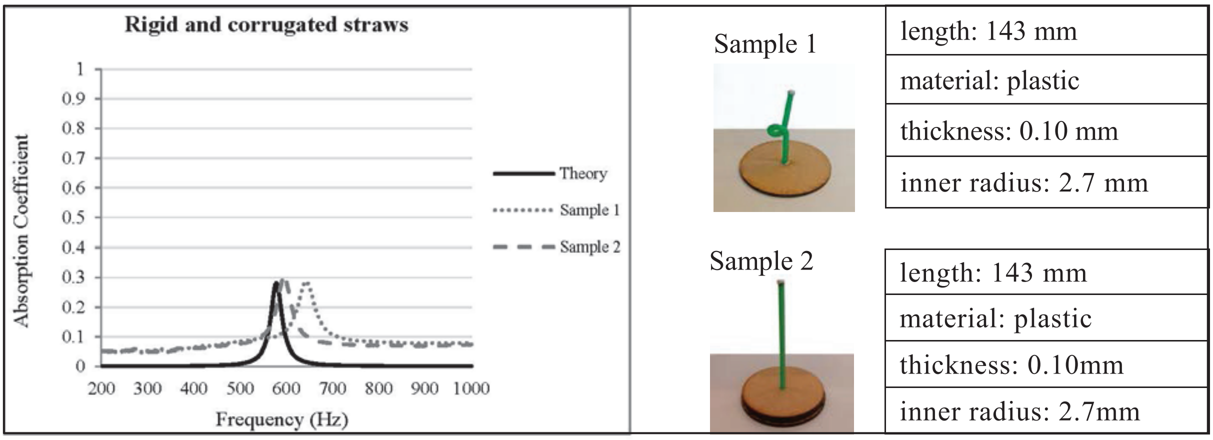
length: 125 mm
material: plastic
thickness: 0.15mm
inner radius: 3.25 mm

Sample 2

length: 125 mm
material: plastic
thickness: 0.05mm
inner radius: 3.25 mm

Figure 1 – different straw thicknesses

The performance of an extendable straw with corrugations is compared to a rigid one in Figure 2. Also this does not seem to influence the absorption performance of the tube. The difference in the peak frequency comes from the inaccuracy in determining the length of sample 1. For this reason extendable straws are not further used in the design proposal.



Sample 1

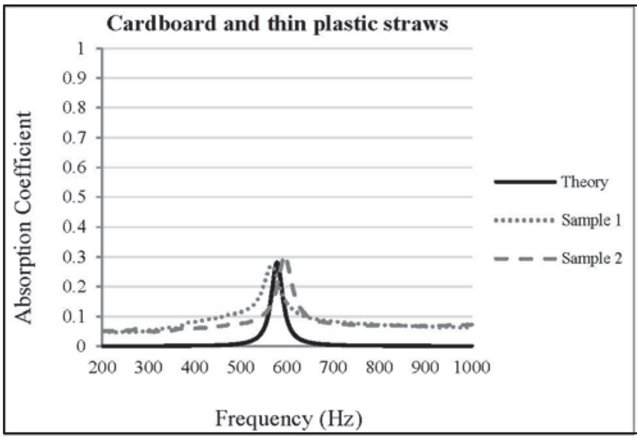
length: 143 mm
material: plastic
thickness: 0.10 mm
inner radius: 2.7 mm

Sample 2

length: 143 mm
material: plastic
thickness: 0.10mm
inner radius: 2.7mm

Figure 2 – different straw lengths

A cardboard and a plastic straw were compared in Figure 3. The performance doesn't seem to be influenced. The 18 Hz of difference correspond to 5 mm of different lengths which might be because of manufacturing inaccuracies.



Sample 1

length: 143 mm
material: cardboard
thickness: 0.10mm
inner radius: 2.7mm

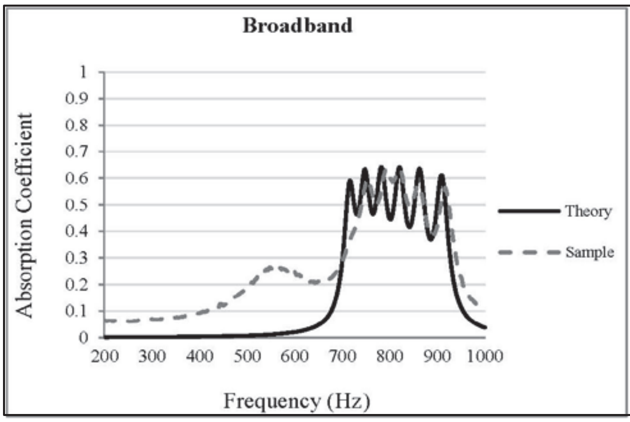
Sample 2

Length: 143mm
material: plastic
thickness: 0.10mm
inner radius: 2.7mm

Figure 3 – different materials

Aiming at the wanted frequency and making the absorption curve as high and wide as possible are the two factors that need to be controlled in a design and optimization process of multiple quarter wavelength tubes. The targeted frequency is easily controlled by the length of the tube and to a minor extent its radius. The peak value and the width of the curve can be controlled by either choosing the appropriate radius or the appropriate number of resonators within a given surface area.

Combining tubes with different lengths allows for achieving broadband absorption, as shown in Figure 4. The small peak around 550 Hz is an inaccuracy from the sample preparation. The peak of 700 Hz is missing from the sample curve. Possible reasons likely are inaccuracies during the manufacturing process.

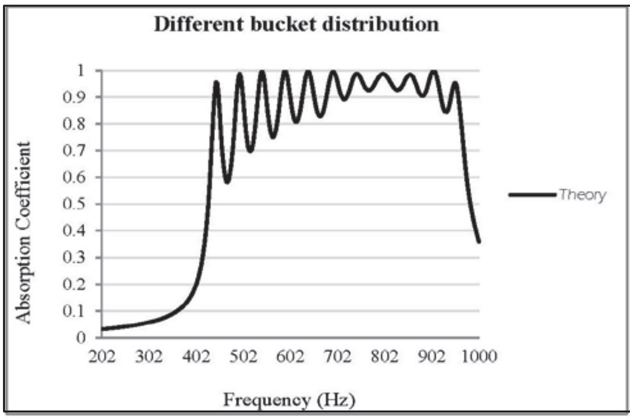


Sample

lengths: 115, 110, 105, 100, 95, 90 mm
material: plastic
inner radius: 3.5mm
number of resonators: 6

Figure 4 – broad (er) band absorption

By increasing the number of tubes tested the absorption performance increases as it is shown in Figure 5. The sample contained 12 groups of drinking straws. Every group consists of 7 straws tuned in every frequency between the range of 400 Hz- 950 Hz with 50 Hz of interval. This configuration is shown only as theoretical result since it wasn't possible to be measured with accuracy. The sample is only shown with the purpose of showing the arrangement of the straws.



Sample

lengths: 213, 189, 170, 155, 142, 131, 121, 113, 106, 100, 94, 89 mm
material: plastic
inner radius: 3.5mm
number of resonators: 12groups x 7pca

Figure 5 – broadband absorption

2.3 Design guidelines

Based on the measurements' results it is decided to make a prototype using thin plastic translucent drinking straws of 7 mm diameter. The choice of radius and material was defined by the availability of the material within the time limit. The targeted frequency is defined by the straw's length and the amount of the absorption is defined by the ratio of resonators on a surface and the radius of the straw.

In figure 6 it is shown how the radius influences the performance of a tube with length *L=0,138 m,* in a sample with cylindrical surface of a radius *r=0,05 m*. Figure 7 presents the variation in absorption depending on different amount of resonators, all of them with length *L=0,138 m,* also in a sample with cylindrical surface of a radius *r=0,05 m.* In both cases there is an optimum size of radius/number of resonators after which the performance starts to decrease.

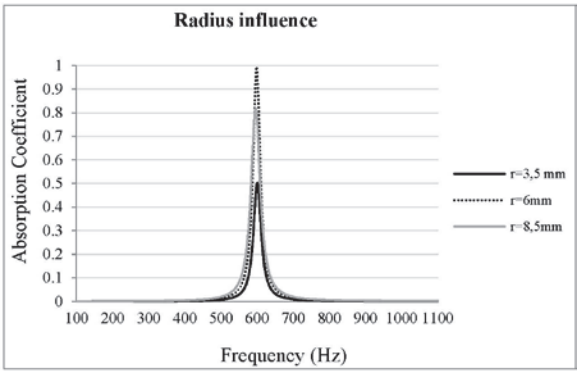


Figure 6 – radii variance

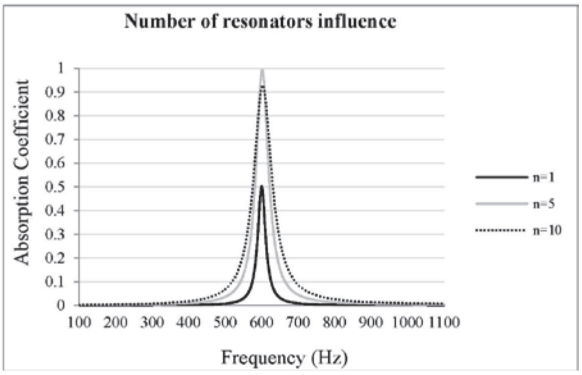


Figure 7 – number of resonators influence

Plastic and cardboard behaved similarly; however, plastic is preferred for the prototype since it offers the translucency effect and can be easily recycled or reused. A rigid design of the straw is preferred so as a higher accuracy in the manufacturing procedure can be achieved.

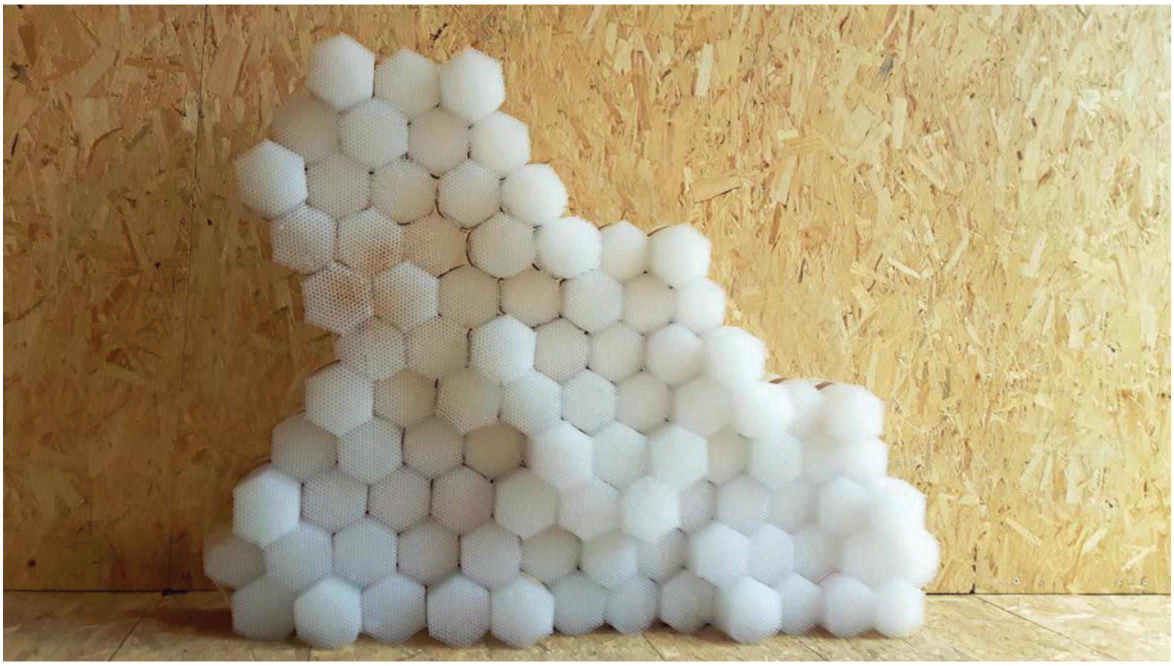


Figure 8 – prototype

Regarding the arrangement of the tubes, the design idea is to arrange them in groups of the same length. Figures 9, 10, 11 show that the straws with the same length are organized in the same way as the samples were tested (Figure 5, 10) but in the final model the scale is bigger (Figure 11).

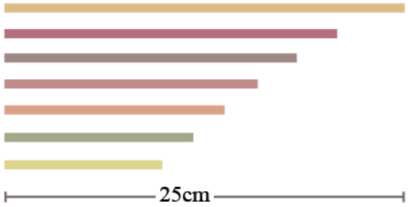


Figure 9 – different straw lengths

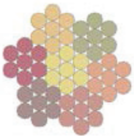


Figure 10 – sample scale

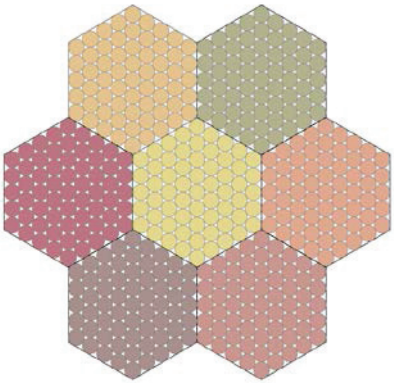


Figure 11 – increased scale

The design proposal has direct connection to the chosen acoustic principle, meaning the use of tubes. The quarter-wavelength tubes need to be closed from one side while the half-wavelength tubes are open from both sides. This information translated into the manufacturing process means that three separate investigations need to take place: the tubes, the way to seal them and the supporting structure. The main target is to save material by making a light, self-supported and low-cost product.

As far as the tubes are concerned, they can be easily massively produced with custom dimensions. Considering that the design addresses a product, the aesthetic value is important. The product is supposed to be used in an interior environment, as a room divider. This means that it needs to provide the users with private space as well as to keep the visual contact. For achieving a screening effect though the sound insulation of the buildup needs further investigation. Open tubes allow a part of light to transfer from one side to the other side of the panel. If a translucent material is also used, this effect is stronger. Last but not least, one of the aims for the design is to allow for re-use of the product in a different space. For this reason no permanent or chemical adhesive is included in the design process. This is important for the design process as the chosen material and the procedure should support the necessary tolerance for integrated connections.

3. Design

3.1 Customizability

According to different acoustic needs of each space, it is possible to have different configurations. Depending on the location of the panel (whether it behaves as a space divider or is put in front of a wall), it is possible to use either the quarter wavelength or half wavelength principle. In practice, the difference is that half wavelength tubes are longer but easier to manufacture since they don’t need a close end.

Below there are examples of proposals according to the placement of the panel and the acoustic performance. The targeted frequencies have a 25 Hz interval, in order to decrease the fluctuations of the curves.

Figure 12 shows a combination of units that can be put in front of a wall which has quite a broadband absorption in the low to mid frequencies. This means that the maximum thickness of the surface is almost 30 cm. Quarter wavelength tubes are used in combination with half wavelength tubes in order to create a more interesting visual effect.

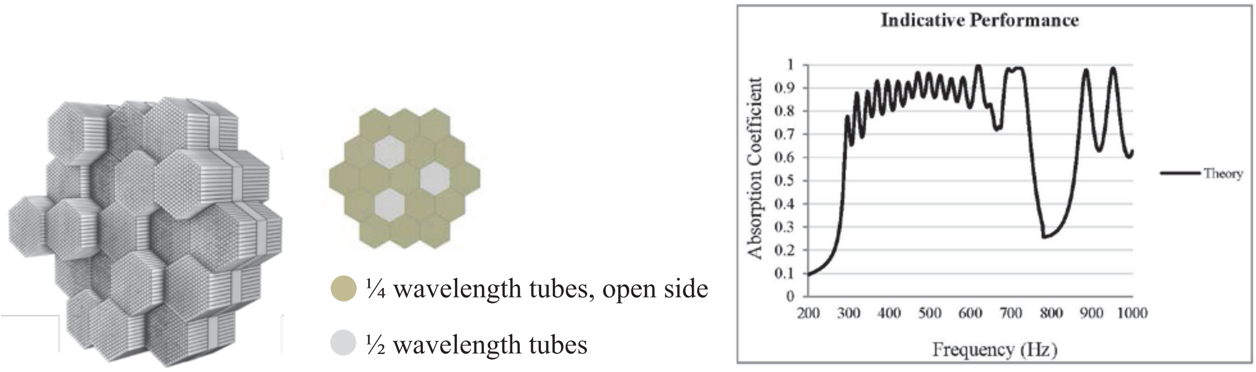


Figure 12 – design proposal

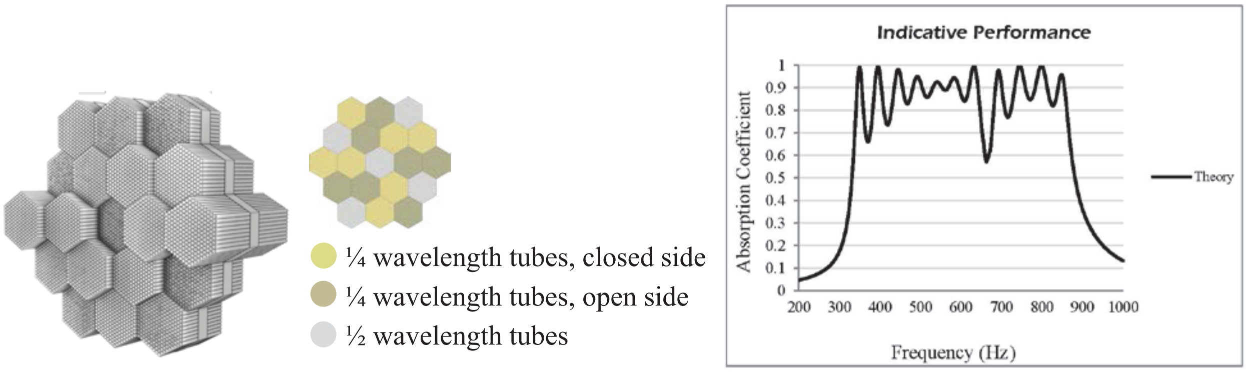


Figure 13 – indicative design

The maximum thickness is 24cm and the acoustic principles used are quarter wavelength tubes for frequencies 350Hz-650Hz and half wavelength tubes for frequencies 700Hz-850Hz. The combination of the two principles gives the advantage of two different visual effects, as the quarter wavelength tubes are closed from one side and the half wavelength tubes are open from both sides.

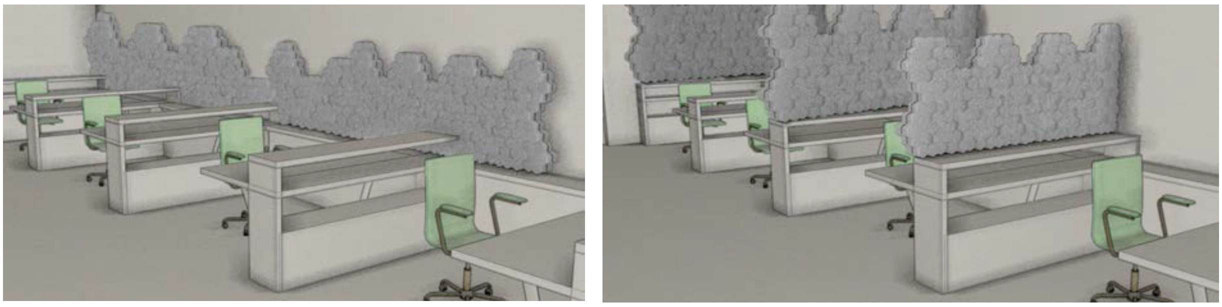


Figure 14 – possible spatial arrangements

3.2 Assembly

The assembly procedure of the big hexagon of 19 units includes the construction of a frame by MDF stripes and metal splits (steps 1-4). As soon as the right shape is made the straws are put in the frame, and the basic form of a 19-unit hexagon is created. In this form the panels are transported to the space of application, where they can be connected with other hexagons by industrial Velcro tape.

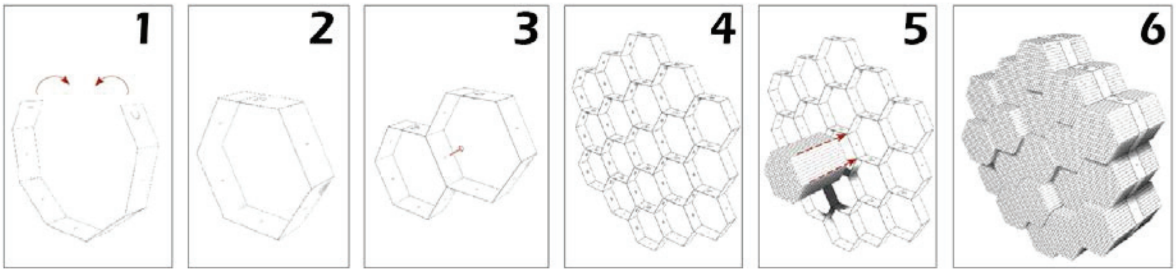


Figure 15 – assembly steps

4. CONCLUSIONS

This paper presented a design concept for a sound absorbing unit based on the quarter and half wavelength tube principle by using a material that is designed for a different purpose.

During literature study, absorbers were further researched as an appropriate approach for decreasing sound levels in mid-high in open-plan offices. Quarter wavelength and half wave length tubes were the acoustic principles further developed due to the high absorption values that can be achieved, the tuning at specific frequencies, fast and low-cost manufacturing process as well as high aesthetical value. In order to define the performance of the drinking straws, the results from two different approaches were compared. A theoretical model in Matlab was developed that can predict the absorption performance of quarter wavelength tubes. At the same time sets of measurements were performed with the impedance tube and then the results are compared to the theory. By conducting various measurements it was confirmed that it is possible to make a prediction with a theoretical model in Matlab for design studies. The different materials tested, like plastic tubes with different thicknesses and cardboard, didn’t seem to influence the performance of the tubes, according to the theory. Combining tubes with different lengths opens up the possibility of creating a broadband absorber. At the same time, the amount of tubes used for the same surface can influence the absorption performance of the absorber, so according to the frequency range targeted and the desired amount of drinking straws it is possible that a different optimized configuration can be created. Absorption values as high as $\alpha=1$ can be achieved by optimizing the ratio between number of resonators and radius of the drinking straws. By decreasing also the interval between the targeted frequencies, a more smooth absorption curve can be achieved.

With further research it is possible to facilitate more the assembly procedure by substituting the drinking straws with honeycomb plates that probably behave in the same way in terms of acoustics but will create blocks that are more robust and easier to stack.

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