Popularization of acoustics through demonstrations shown on the Open Door Day of the Faculty of electrical engineering and computing in Zagreb, Croatia

Marko Horvat, Kristian Jambrosic, Miljenko Krhen, Antonio Petosic

POPULARIZATION OF ACOUSTICS THROUGH DEMONSTRATIONS SHOWN ON THE OPEN DOOR DAY OF THE FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING IN ZAGREB, CROATIA

Marko Horvat Kristian Jambrošić Miljenko Krhen Antonio Petošić
University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia
marko.horvat@fer.hr

ABSTRACT

Popularization of science has a long tradition on the University of Zagreb. The Faculty of Electrical Engineering and Computing follows this tradition by organizing its own Open Door Day. The visitors range from small children and their parents, through pupils from primary and secondary schools, future students, all the way to people in the golden age of their lives. They are given the opportunity to get an insight into various fields of electrical engineering, computing, mathematics, and physics. To achieve this goal, many different exhibits are shown, and demonstrations are organized in a funny and easy-to-understand manner. As a part of the Faculty, the Department of Electroacoustics participates by teaching its visitors some basic facts about various sound- and audio-related phenomena. This paper presents the guided tour the visitors are given when they visit the Department of Electroacoustics. The demonstrations include room modes in a rectangular room, acoustic levitation achieved by an ultrasonic standing wave, and an ultrasonic surgical blade usually used in neurosurgery. Different room acoustical conditions are demonstrated by visiting a rather reverberant classroom, the anechoic chamber, and the acoustically treated listening room. The listening room is also used for demonstrating the (over)exposure to noise and the harm that comes from it, as well as for showing the basics of digital audio processing. Spatial sound is demonstrated by listening to binaural recordings of moving sources. A simple hearing test lets the visitors find the highest frequency of their hearing range. Shepard tones are demonstrated as an example of a sound illusion. The paper gives a detailed description of each demonstration, with the background story and the key pieces of equipment required to make the demonstrations work.

1. INTRODUCTION

The Open Door Day at the Faculty of Electrical Engineering and Computing is a perfect opportunity to display the state-of-the-art in all the different fields of research and teaching that currently exist on the Faculty. In most cases, research teams strive to show the most recent advancements in their respective fields, and to show the results in form of a final product, or the equipment used in research, or both. The emphasis is put on current research to attract potential students, whereas the educational component is only marginally present.

The Department of Electroacoustics has adopted a different approach to this event. Since sound is a phenomenon that is constantly present in people's lives, the members of the department have chosen to create an educational tour. The goal is to try to present and explain some of the most basic phenomena related to sound that people encounter daily, but are unaware of them. The exhibits are devised to explain the phenomena from the field of room acoustics and noise. Additionally, the tour extends to the field of ultrasound as something that is found in everyday life, mostly in the field of medical diagnostics. Simple, but engaging demonstrations make only a hint on the versatility of ultrasound and all its uses. The emphasis is put on educating the visitors on the basics of sound-related phenomena, rather than displaying the most recent advancements in research.

2. DEMONSTRATIONS

2.1 Room Modes

The demonstration of room modes is a very effective way of showing the influence of the room on the overall listening experience. The demonstration itself is made in an ordinary classroom. The room is quite reverberant at low frequencies, as there is very little damping in that frequency range. For the purpose of the demonstration, the room is cleared of tables and chairs, so that the visitors can move around freely. The dimensions of the room are 7,20 m x 6,60 m x 3,2 m, which gives the lowest modes in the room at the frequencies of 23.8 Hz (1,0,0), 26 Hz (0,1,0), 35.2 Hz (1,1,0), 47.6 Hz (2,0,0), and 52 Hz (0,2,0). The tangential mode (1,1,0) has been chosen as the one to be shown in the demonstration. The reason for this is that the axial modes (1,0,0) and (0,1,0) are quite close to each other due to the almost square-shaped floor area of the room, and cannot be clearly distinguished from one another. More importantly, they cannot be properly excited with the low-frequency loudspeakers used in the demonstration, as the corresponding mode frequencies are below the usable frequency range of these loudspeakers. The higher axial modes (2,0,0) and (0,2,0) can be properly excited, but

10.48465/fa.2020.0159

they are also too close to each other. The chosen tangential mode (1,1,0) is quite separated from adjacent modes, and its frequency of 35.2 Hz is well within the frequency range of the used loudspeakers.

The modes of this very laboratory room and their formation were investigated in an earlier research [1] by measuring a large number of impulse responses in a scanning grid laid out across the floor area of the room. The chosen (1,1,0) mode is clearly visible in Figure 1.

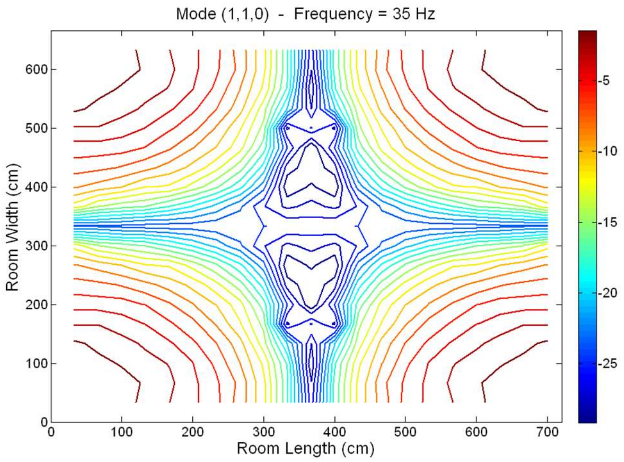

Figure 1. The (1,1,0) mode chosen for demonstration, measured in an earlier research [1]

The room where the demonstration takes place is shown in Figure 2.

Figure 2. Demonstration of room modes

The demonstration starts with a back-story about the listening experience in shoebox type rooms of ordinary size, namely, how the low-frequency content changes depending on the position of the loudspeakers and the listener inside the room. The visitors are encouraged to think about their listening experiences at home, and they often conclude, “There is lots of bass in the corners and not so much in the centre of the room”. Depending on their knowledge of physics, the visitors are then informed, in more or less detail, that ordinary shoebox-type rooms are, in fact, resonators whose resonance frequencies depend solely on room dimensions. The concept of standing waves is explained to them, with the emphasis on “standing”, meaning that the antinodes and the nodes of the standing wave, as the areas of maximum and minimum level or “loudness”, do not change their positions. The fact that all modes have their maximum “loudness” in the corners is revealed to the visitors, thus confirming their previous experiences with the “quantity of bass” in these positions. They are told that they will be able to experience an extreme situation by listening to one particular mode at a specific frequency, instead of experiencing many modes simultaneously while listening to music. The mode shape is illustrated on the blackboard, so that the visitors have an idea what to expect.

The chosen mode is demonstrated by placing a subwoofer on a small trolley and putting it in one of the corners of the room, so that the mode is excited as much as possible. The visitors are encouraged to move freely around the room, in order to see (or, better yet, hear) for themselves that the standing wave is indeed formed in the room in the shape illustrated on the blackboard. For greater impact, the mode is excited at high volume, resulting in the sound pressure level of 110 dB in the antinodes. The measured sound pressure level in the nodes is 86 dB, which gives a level difference of 24 dB. The resulting loudness sensation goes from “very loud” in the antinodes to “fairly soft” in the nodes. The visitors are alerted to the fact that their position in the room has a great influence on how much they will actually hear a certain room mode.

To demonstrate that the position of the loudspeaker also has a great influence on the strength of a certain room mode, the subwoofer is pushed to the centre of the room, and it is shown that a source placed in a minimum of the standing wave at a certain room mode cannot excite that particular mode. The subwoofer is then pushed along the nodes of the standing wave to demonstrate that the source can be put anywhere in the node area, in order not to excite the mode. The subwoofer is then pushed into the corners of the room to show that the source can be placed in any antinode to excite a mode.

The visitors are then explained that the sounds they hear in the adjacent regions of the standing wave, defined with its nodes, are actually out-of-phase with each other. The mode is excited by the subwoofer once more and the visitors are encouraged to find the nodal planes that separate these regions, so that they listen to the sound in one region with one ear, and the sound in the adjacent region with the other. At this point, some of them say, “Hey, this is like wiring the loudspeakers on my stereo system wrong!”, and they are then explained that the two effects are indeed the same.

The second part of the demonstration focuses on the impact of two sources in the room on the overall state of the room mode they excite. It involves using two identical subwoofers, one still sitting on a trolley, and the other one placed in one of the corners of the room. The visitors are asked if the two subwoofers will always be louder than a single one. The meaning of "in-phase" and "out-of-phase" operation of the two subwoofers is explained with an example of two men working with the same saw simultaneously. Then it is demonstrated that two subwoofers working in-phase and positioned in the same corner will indeed produce a louder sound than each of them would individually. The explanation is given that each of them produces its own standing wave pattern, and the result is the superposition of the two, which indeed gives 6 dB higher sound pressure level. The movable subwoofer is then pushed into the adjacent corner of the room, which yields a much lower sound pressure level than the one produced by each of the subwoofers individually. The visitors are explained that in this case, the subwoofers still work in-phase, but their individual standing wave patterns are out of phase, and the superposition of the two is actually destructive. The question put to the visitors is how louder sound can still be achieved with two subwoofers. At this point, they usually guess both solutions. The first one is that subwoofers stay where they are, but have to work out of phase to produce two standing wave patterns that are in phase, in order to get a constructive superposition. The second solution is that the subwoofers continue to work in phase, but they need to be put in two regions of the standing wave that are also in phase, in this case, in diagonally opposite corners. Both solutions are demonstrated and confirmed to be valid. The conclusion of this section is that multiple sources of low frequencies in the room, such as a pair of floor-standing loudspeakers or a pair of subwoofers will only add to the complexity of the overall low-frequency response of a room in which they are placed.

At this point, the demonstration is finished.

2.2 Acoustic Levitation

This demonstration displays the acoustic levitation effect, in which particles are made to levitate using ultrasonic waves. To achieve this, an ultrasonic transducer with the resonance frequency of its thickness mode of 30.3 kHz is used. The transducer is a Tonpilz-type ultrasonic radiator with a circle-shaped flat radiating surface. It is positioned above the metal plate of the stand used to hold it in place, so that its radiating surface is parallel to the plate. This way, a simple axial standing wave is formed between the parallel surfaces. The distance between them is initially set to 6-7 centimetres, but it needs to be finely tuned so that it be equal to a multiple of the half-wavelength at the resonance frequency of the transducer. It is explained to the visitors that the transducer operates at its resonance frequency to yield the highest possible amount of mechanical vibrations for a given input electrical power. The fine-tuning of the distance required to meet the aforementioned condition is essential for the forming of a stable standing wave pattern. At the stated resonance frequency of the transducer, the wavelength is only 11.32 millimetres. The distance between two adjacent pressure nodes (minima) or antinodes (maxima) of the standing wave is equal to half the wavelength, i.e. 5.66 millimetres. The distance between a pressure node and an adjacent pressure antinode is a quarter of the wavelength, i.e. 2.88 millimetres. Therefore, to demonstrate acoustic levitation with this setup, particles of a similar size must be used. Therefore, this demonstration setup uses individual particles of expanded polystyrene that are dug out from larger pieces. Their mass is small enough to facilitate a successful demonstration, as the resulting downward gravitational force needs to be counterbalanced by the radiation force exerted on the particles by the ultrasonic wave of sufficient amplitude. The radiation force is the direct consequence of the spatial gradient of the sound pressure above and below the particle. To yield an upward radiation force, the pressure above the particle needs to be lower than the pressure below it. To achieve this, the particle is initially placed in a pressure node of the standing wave. Its mass causes it to sink below the node, but only to a point where sufficient pressure gradient is reached, as the bottom of the particle is now in or near the pressure antinode, and the top is in or near the pressure node. This simple setup allows the particles to levitate in fixed positions. The visitors are encouraged to find video clips on the internet, showing sophisticated setups that allow heavier objects not only to levitate, but to be moved around as well. The demonstration is shown in Figure 3.

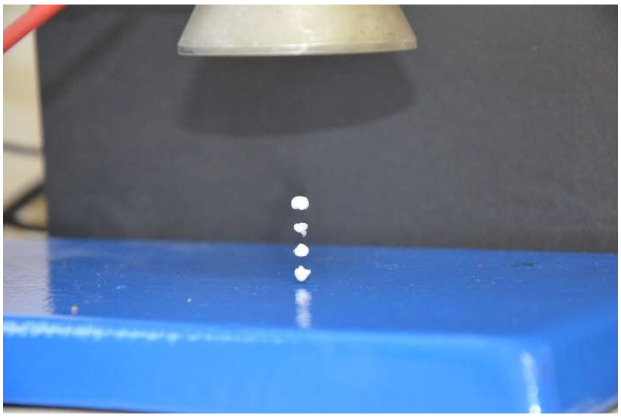

Figure 3. Acoustic levitation

The setup itself consists of a signal generator capable of generating the sinusoidal signal with the frequency that matches the resonance frequency of the transducer. The frequency of the generated signal can be finely tuned. The generated signal is fed to a power amplifier that provides excitation for the transducer. In this demonstration, the power delivered to the transducer operating in resonance is kept low, i.e. 2-3 W at most, so that the sliding of the resonance frequency due to nonlinearities and/or thermal effects is avoided. For this reason, the resulting ultrasonic wave is strong enough to levitate very light particles, such as the aforementioned expanded polystyrene. The voltage over the transducer and the current through it are constantly monitored by means of a voltage and a current probe, respectively, both connected to an oscilloscope. Such a setup facilitates a fast way of finding the resonance frequency of the transducer simply by changing the frequency of the generator and monitoring the voltage and current waveforms on the oscilloscope. Once the resonance condition has been achieved, the voltage and current will be in phase. The setup also facilitates the correction of the operating frequency, should the need arise due to minor changes in the resonance frequency of the transducer.

Once stable operating conditions have been achieved and a stable standing wave has been formed, the particles can be placed into the standing wave field. The easiest way to do this is by using a pair of tweezers to hold the particle. The particle can be put in any pressure node of the standing wave. If a particle is simply rolled on the metal plate into the standing wave field, it will assume a fixed position in the lowermost pressure node, i.e. the one closest to the metal plate. Other particles can then be easily added on top of each other, having in mind that their centres should be half a wavelength apart, i.e. 5.66 mm. If the distance between the transducer and the metal plate was not tuned accurately enough, the standing wave will not be formed as expected. In this case, either it will be impossible to put a particle in a stable position, or the particle will strongly vibrate in its position (at best). If the particles are not round enough, they will tend to rotate in their positions.

2.3 The Anechoic Chamber

The visit to the anechoic chamber is always a treat for the visitors. It is advertised as “the quietest room on the Faculty and beyond”, and many visitors have already heard that there is such a room. As the net dimensions of the chamber are only 2 meters x 3 meters x 2 meters, the visitors are divided into small groups. The chamber itself is shown in Figure 4.

Before entering the chamber through another laboratory room, the visitors are encouraged to pay attention on how the voice of the guide and the handclaps he makes are heard in an ordinary acoustic environment. Upon entering the chamber, the guide starts speaking and claps his hands once again, thus pointing to the unusual and unexpected acoustic conditions inside as the result of extreme acoustic treatment. It is explained to the visitors that the room is well insulated from the rest of the building, which makes it very quiet inside. The purpose of the wedges that cover all the surfaces in the chamber is also explained to the visitors. In this particular case, the wedges are made of glass wool stuffed into bags of acoustically transparent fabric, and the proper form is achieved by inserting a wire frame into each bag.

Figure 4. The anechoic chamber

The visitors are informed that the ultimate goal is to form a noise-free and reflection-free environment inside the chamber, i.e. to have the free-field conditions inside. The back-story is given on the need to have such an environment in specific types of measurements that require free-field conditions, such as microphone or loudspeaker measurements, which require only require direct sound from the source to the receiver, and would be corrupted by reflections from the surfaces of the room. It is also pointed out that the results of such measurements would be unusable if the measurements were made in an ordinary room, due to the reflections from the surfaces that ultimately lead to reverberation, standing waves and other acoustic phenomena. It is also said that these measurements could also be made outdoors, if a spot far from any reflective surfaces can be found, so that free-field conditions are established. However, the influence of background noise and meteorological conditions would be substantial.

Many visitors report that they have a “strange feeling” inside the chamber, from “pressure building up in their ears” to feeling “a little bit claustrophobic”. Some of them ask if it is true that their hearing “gets better” inside, while some state that they could spend some time inside in order to rest. It is then explained to them that the acoustic environment inside an anechoic chamber is unlike any they will encounter in everyday life. Normally, the human hearing is constantly bombarded with all kinds of sounds, each of which carries a possibly relevant information. The total absence of these sounds is what causes different responses by people. Furthermore, having spent enough time in such a quiet environment, a normal, healthy hearing system will adapt and become more sensitive, just as the eye does when there is very little light.

As they are shown out of the anechoic chamber, the visitors are encouraged to listen to the difference between the acoustics in the chamber compared to a normal laboratory room. The demonstration ends here.

2.4 The Listening Room

The listening room of the Department of Electroacoustics is primarily meant to host all kinds of listening events, ranging from listening tests to be used in scientific research to informal gatherings meant for assessing the quality of loudspeakers and other audio components. On the Open Door Day, the room is exhibited as an example of an acoustically treated space, in order to make the acoustical conditions inside resemble the ones found in living environments, where people usually listen to music. With the floor area of 73 m^2, it is much larger than the average living room. It can host up to 10 listeners for a high-quality listening experience, and even more for demonstrations, lectures, etc. The listening room is shown in Figure 5.

Figure 5. The listening room

Firstly, the purpose of acoustic elements hanging on the walls of the room is explained to the visitors. The basics of room acoustical phenomena of reverberation and the effect of putting different finishing materials on the surfaces of the room is explained as well. Examples from everyday life are given; e.g., the visitors are encouraged to think about the situation where they have to empty a room in order to repaint it, and how that room "sounds" when it is empty, compared to the case when it is fully furnished. The visitors are also asked if they had ever thrown a party in a basement or a similar space with concrete surfaces, and are encouraged to remember how music sounds in space like that. Everyday examples of different acoustic conditions are given, e.g. long reverberation in churches, excessive reverberation in classrooms, etc. During organized visits with schoolchildren, the teachers often complain that the acoustics in classrooms is inadequate. It is explained to them that relevant research has already established a direct link between bad acoustics and reduced learning capacity of pupils. Moreover, they are told that bad acoustics results in all kinds of health problems for teachers as well.

A part of the tour inside the listening room includes a short demonstration of what it means to listen to a sound with the sound pressure level of 100 dB. For this purpose, a sound level meter is placed in the room, and a suitable excerpt of music is reproduced through a pair of PA loudspeakers, which are connected to a microphone and a line source of music through a digital mixing console. A very common response given by the visitors is "This is not so loud!". The visitors are then alerted to the risk of hearing loss that comes from overexposure to sounds with high sound pressure levels, especially because the risk comes from voluntary exposure by visiting clubs and concerts, and even more by wearing headphones. It is pointed out that hearing damage comes gradually, but is also cumulative and irreversible. The visitors are made aware that it is quite easy to obtain very high sound pressure levels on headphones and not even notice it, which only makes it even more dangerous to use them. The term "daily dose of sound" is explained to the visitors. It is pointed out that sound/noise with the level of 85 dBA can be listened to over a period of 8 hours [2], and that this represents the allowed daily dose. It is also explained that if the level is raised by only 3 dB, it actually means that the sound energy is doubled, and the exposure time needs to be cut in half, and this is repeated for every 3 dB increase. This rule yields the maximum exposure time of 15 minutes for the sound demonstrated earlier and assessed as "not so loud". It is then pointed out that the sound pressure level in clubs/concerts, or on headphones, can easily exceed 110 dBA, which reduces the allowable exposure time to minutes or even seconds. At the end, if a group of young schoolchildren takes the guided tour, they are encouraged to stand around the sound level meter in a circle, and to yell as loud as they can. The resulting sound pressure level is usually between 105 and 112 dBA.

The last part of the tour in the listening room is focused on demonstrating different audio effects. Since the digital mixing console has a number of built-in effects, it is the crucial tool for this demonstration. The demonstration uses live speech of the guide, who speaks into the microphone. The effects of bad acoustics are demonstrated by putting short reverberation on the speech signal and gradually increasing it over time. This is meant to show how reverberation influences the speech intelligibility. Another effect demonstrated to the visitors is the multitap delay, which produces multiple echoes that sound quite impressive on the speech signal. The last effect is the pitch change, also demonstrated on the voice of the guide. This effect always makes the visitors laugh, and they are usually quite eager to try it out themselves.

At the very end, the visitors are encouraged to ask about anything that interests them, what the guide may have omitted during the demonstration. Since the listening room is used for equipment storage, the most interesting pieces are different omnidirectional sound sources stored inside, and their purpose is explained to the visitors. A miniature portable anechoic chamber (the “egg”) also catches the eye of the visitors. It is explained to them that it functions the same as the full-size anechoic chamber they had visited a little while ago, but this one is used for measuring hearing aids and other similarly sized pieces of equipment.

2.5 Ultrasonic Surgical Blade

Another demonstration based on ultrasonic phenomena is the ultrasonic surgical blade. It was developed as a prototype for devices that to be used instead of classic surgical scalpels.

The system consists of an ultrasound generator coupled with a power amplifier, and a hand piece with a surgical tip. The only parameter that can be adjusted is the amplitude of the excitation signal, and, consequently, the available mechanical power. The power is applied to the hand piece via a dedicated footswitch, so that the operator’s hands are kept free. The hand piece itself consists of ultrasonic transducers built as piezoceramic rings, the front and backing mass, the concentrator, and the sonotrode. The tip of the sonotrode in this particular case has a solid curved tip with a diameter of 5 mm.

The hand piece is designed as a resonant device, to maximize the efficiency of conversion from electrical to mechanical/acoustical energy. To facilitate the stability of system, near-resonance operation has been chosen rather than in-resonance operation.

Therefore, the transducer is driven at the excitation frequency of 25 kHz, i.e. near the series resonant frequency of the longitudinal vibration mode, in order to maximize the tip displacement, given all the constraints.

The schematics of the hand piece is shown in Figure 6.

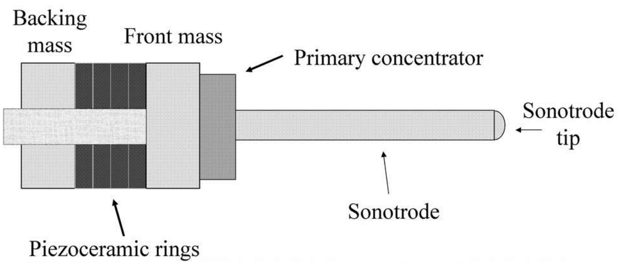

Figure 6. The hand piece of the ultrasonic surgical blade

Besides the surgical blade itself, additional equipment is used in the demonstration, i.e. a glass of water, a piece of wood, and a thermovision camera.

The demonstration begins with a back-story about ultrasound: what it is, why we cannot hear it, and where and for what it is used (medical tests based on ultrasound, non-destructive testing of materials, ultrasonic cleaning, and many other uses). The operation of the surgical blade is then shown, first on water, then on wood. As there is a considerable amount of mechanical/acoustical power involved, submerging the sonotrode tip into water leads to cavitation. The nature of the phenomenon is explained, and various examples are given, both when the phenomenon is utilized and put to good use (e.g. cleaning), and when it is an unfortunate side effect (e.g. damage to ship propellers). Another example that shows not only the amount of energy transferred to the treated medium, but also the energy density on the tip of the sonotrode, is demonstrated by pressing the sonotrode tip against a piece of wood. At this point the energy transfer is highly efficient, resulting in a swift increase of temperature localized at the contact point. In fact, the wood is quite easily burnt, although the demonstration does not yield an open flame.

In both cases, the swift increase in temperature demonstrated using a thermovision camera. It clearly shows a hot spot at the contact point of the sonotrode tip and the material, especially in the demonstration with wood. The visitors always show a great interest for the thermovision camera. Therefore, they are allowed to use it to capture the temperature of other objects as well, such as windows, their hands or heads, etc.

2.6 Other exhibits

The remaining exhibits have been added quite recently to the described tour. One of the exhibits allows the visitors to experience binaural listening by listening to recordings made using a dummy head. The alternative is to connect the dummy head directly to a sound reproduction system that uses headphones, so that binaural sound can be experience in situ, and in real time. To accommodate several listeners simultaneously, a distribution headphone amplifier is used, to which several pairs of headphones are connected. Another exhibit is set up to test the upper frequency of the listener’s hearing system, simply by employing an upward sine sweep. The listener is instructed to press a button on the user interface as soon as they cannot hear the reproduced sound anymore. The corresponding frequency of the sound signal is recorded and displayed as the result of the test. The final exhibit is a simple demonstration that consists of reproducing the Shepard tone [3] as a form of an acoustical illusion. All three exhibits are presented in the entrance part of the Faculty, so that the visitors are encouraged to visit the Department of electroacoustics, which is secluded from the main exhibition space. Since most exhibits are displayed in the main space, the visitors spend the most of their time there. Due to the sheer number of people and the reverberance of the space, the resulting noise level is considerable. Even though closed headphones are used in all three exhibits, the noise still limits the listener experience.

3. CONCLUSIONS

This paper presents the exhibits shown by the Department of Electroacoustics at the Open Door Day of the Faculty of Electrical Engineering and Computing in Zagreb, Croatia. The visitors are usually very satisfied and impressed with what they are shown, judging from their impressions that are collected in various ways. Moreover, the Department of Electroacoustics has won several Best Presentation awards for these exhibits, given based on visitors' judgments, which proves the popularity and appeal of the tour.

4. REFERENCES

[1] M. Horvat, K. Jambrošić, and H. Domitrović: "The examination of the influence of standing waves on reverberation time measurements in small reverberant room", Proc. of Acoustics'08, pp. 4459–4464, 2008.

[2] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:042:0038:0044:EN:PDF, accessed on 12 March 2020

[3] https://en.wikipedia.org/wiki/Shepard_tone, accessed on 13 March 2020