Acoustics for architects: A potpourri of undergraduate and graduate level teaching styles, tools and in-course projects

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JASA ARTICLE

Acoustics for architects: A potpourri of undergraduate and graduate level teaching styles, tools and in-course projects[a]

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ABSTRACT:
Acoustics is one of the basic environmental comfort factors both in indoor and outdoor spaces. Students of architecture need to confront this theoretical field at some phase of their education. The main focus of this study is to provide a discussion platform of tools and teaching styles in architectural acoustics education of future architects, by depicting approaches that can motivate students and provide them a long-lasting understanding of the phenomena. Accordingly, a long-term experience in acoustics classes with undergraduate and graduate level students, mainly from departments of architecture of two prominent Turkish universities, is exemplified. Course contents of architectural acoustics programs are described, different models and methods of teaching are discussed, and last, selected projects, specifically those having an academic output, are presented. The study also aims to highlight some techniques and approaches that can be employed in acoustics education with limited technological tools, simply by active inclusion of the design background and creative thinking of the architecture students in this applied research area.
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I. INTRODUCTION

Architecture is a multidisciplinary field that bridges art, science, and engineering. There are various contributors for a successful architectural end product. As Vitrivuis stated in his famous trio, the core concerns are "utilitas" (utility), "firmitas" (strength), and "venustas" (beauty). Sound in architecture is an intangible aspect relating to both utility and beauty of the space. Utility comes from the satisfaction of specific function in a room in terms of auditory comfort as well as health when noise is a factor in a specific environment. The beauty of the auditory environment can be considered as an indoor soundscape of a symphonic music hall, or an outdoor soundscape of an urban park. The architectural acoustics at this point is in charge of providing the aural aesthetics or functionality, while limiting noise as a source of discomfort by bridging again the current knowledge in art, science and engineering.

Architectural acoustics is initially included in the curricula of architecture departments at the undergraduate level at various stages, while there are several interdisciplinary programs as part of the universities in the world that provide a graduate level of education. The undergraduate level of education aims at introducing the basic concepts of acoustics to architecture students so that they can apply this knowledge in their multi-model design process. The graduate level of education is basically research oriented, but at the same time strengthens and flourishes the theoretical background of the students for their future field-practice. By that, they either choose to pursue their academic carriers or may opt to become experts in architectural acoustics practice.

Some previous research on the role of acoustics in architectural curriculum highlights the presence of significant differences among room acoustics and noise control education, considering the weight and content of acoustics courses at different universities (Yüksel Can *et al.*, 2009). For this specific sample group comparing different schools from Turkey, Italy, France, and the UK, the reason is not essentially to promote the available facilities or faculty present in the universities but instead the general philosophies of the schools and also the duration of the architectural education in different countries. It is for sure that in a broader perspective, not every school in the world may have a sufficient number of trained experts on the topic or may not have an acoustics lab to further demonstrate different subjects. For this reason, the methods and materials in architectural acoustics education are a significant subject that can be better developed by sharing ideas in the academic platform.

Kang (2008) introduced simple simulation and calculation tools that he uses in the courses to better explain acoustical principles to architecture students in concepts related to barrier effects, sound distribution in street canyons, reverberation time (RT), absorption by perforated materials, and urban soundscape. Technology progresses very fast, and today, even applications of smartphones provide a variety of demonstration tools to be utilized in classes. On the other hand, real-time room acoustic simulation tools such as RAVEN (Schröder and Vorländer, 2011), as applied in the

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virtual reality system of RWTH at Aachen University, is another edge of the technology.

Yet, the common view of different educators is that simulations over case studies, site visits, and if possible/available, performing *in situ* tests, are the most attractive and instructive ways of grounding the basic principles and issues in room acoustics and noise control education, both at undergraduate and graduate levels (Busch-Vishniac and West, 2007; Beyazıt and Hohman, 2012; Meriç and Çalışkan, 2013; Llorca-Bofí *et al.*, 2020). Lectures are also highly appreciated by the students as a primary way of getting into the subject (Meriç and Çalışkan, 2013). However, it is also noted that the theory should not be overwhelming to the students and practical issues in relation to the design process should be accentuated (Sygulska, 2021). Questionnaires are also effective for enabling students to think about the link between objective measures and subjective parameters, hence the real feeling and the perception (Llorca-Bofí *et al.*, 2020).

Kitapçı (2019) reviewed the acoustics education in interior architecture departments of different universities in Turkey and suggested a new framework with a focus on multi-sensory design approach by the introduction of soundscape research steps in course curriculum. Application of soundscapes, the context, and the connection of different sensory items in generative design process is another way of focusing the attention of architectural students towards the sound; as a major actor and inspirational concept (Sheridan and Lengen, 2003; Llorca *et al.*, 2018). Similarly, Milo (2020) states that tasks related to listening and documenting sonic environments within the framework of soundscape could provoke the interest of students in acoustics design.

In this study, a long-term experience in acoustics classes with undergraduate and graduate-level of students, mainly from departments of architecture of two prominent universities in Ankara, Turkey, is exemplified through different in-course assignments and projects. The aim is to contribute to the common discussion ground of the teaching styles, methods, and tools in architectural acoustics education. Initially, the course contents of architectural acoustics programs, different models, and methods of teaching are described, selected projects specifically those having an academic output are presented, and last the overall teaching styles are compared by including student feedback in the following sections.

II. TOPICS IN ARCHITECTURAL ACOUSTICS

The contents of acoustics education in the architecture departments of universities in Turkey have already been discussed in a couple of publications (Meriç and Çalışkan, 2013; Yüksel Can *et al.*, 2009). The recent enforcement of noise control regulation for buildings in Turkey (The Turkish Regulation on Noise Control for Buildings, 2018) hopefully will motivate more schools to expand their course contents on acoustics and accordingly the schools will increase the size of academic faculty on the field. The availability of sources and academic staff with expertise on the topic is very different in universities around the country, which especially has an impact on the number of graduate programs on architectural acoustics. This study discusses in detail two graduate elective courses from Middle East Technical University and one undergraduate must course from Bilkent University in Ankara.

In the Middle East Technical University under the Building Physics graduate program (M.Sc. and Ph.D.) two elective courses have been offered since 1998, as long as there is a sufficient number of students to enroll each semester. BS 575 Acoustics in Architecture I, is offered in the Fall semester. This course covers the basics of sound propagation and then has its emphasis on room acoustics concepts accompanied by a project assignment of yearly slight variations, but the concentration is on the design of an acoustically demanding space like a performing art or a multi-purpose venue. The other course on acoustics, entitled BS 576 Acoustics in Architecture II, is offered in the Spring semester. Its basic objective is to construct a knowledge base for students in order to teach the environmental noise issues and sound insulation in the buildings (Meriç and Çalışkan, 2013).

The department of Architecture at Bilkent University is fairly young (10 years old). Hence, there is no elective course for the graduate school that specifically focuses on acoustics yet. However, in some other courses as ARCH 515, entitled Topics in Architectural Technology, room acoustics and noise concepts are discussed in different modules together with other topics including light and color, energy efficiency and user comfort, materials and sustainability, intelligent facades, etc. The course has shaped slightly differently every semester in accordance with the background and research interests of students enrolled in the course. The major course in the department is an undergraduate must course, namely, ARCH 341 Architectural Lighting and Acoustics, which covers one half semester lighting in architecture and the other half architectural acoustics. This is almost the maximum course hours dedicated to acoustics education in the architectural curriculum when different universities are compared. The course was previously named Environmental Technology I and used to include more topics in relation to building physics, thus less hours allocated for acoustics. Later, those other topics, including fire and energy efficiency, were removed from ARCH 341, which opened in the Fall semester (6th semester of the undergraduate program) and collected under ARCH 342 Environmental Technology II, which is available in the Spring semester (7th semester of the undergraduate program).

The course entitled IAED 341 Architectural Acoustics and Fire Safety, is a course offered to students from the Interior Architecture and Environmental Design department of Bilkent University, since 1987, which was previously called Building Performance. The acoustics modules of both ARCH 341 and IAED 341 offered underneath the same faculty eventually have similarities and common grounds. The major difference is that the "Lighting" module of one course is replaced with "Fire Safety" in the other. Within the scope

TABLE I. Contents of courses BS 575, BS 576, and ARCH 341 offered at Middle East Technical University (METU) and Bilkent University.

METU – Graduate Program in Building Science	METU – Graduate Program in Building Science	Bilkent University – Graduate Program in Architecture
BS 575 - Acoustics in Architecture I (3 hours per week, 8 ECTS[a] credits)	BS 576 - Acoustics in Architecture II (3 hours per week, 8 ECTS[a] credits)	ARCH 341- Architectural Lighting and Acoustics (3 hours per week, 5 ECTS[a]) credits)
Basic concepts (sound, amplitude, frequency, levels etc.)	Introduction to noise and its effects, review of basic acoustical concepts	Basics of sound and vibration
Hearing and perception of sound	Noise metrics and parameters	Absorption, reflection and diffusion; sound absorptive materials
Introduction to room acoustics	Sound level meters and noise measurements	RT
Objective acoustical evaluation measures	Noise sources and outdoor noise propagation	Rooms for speech, sound path diagrams
Forms and acoustical design criteria	Turkish noise legislation	Rooms for music
Acoustics of small rooms	Reverberation control	Environmental noise control
Modelling and acoustic simulation of spaces	Sound transmission and isolation	Speech privacy

[a]European Credit Transfer and Accumulation System (ECTS).

of this paper, the course contents of BS 575, BS 576, and ARCH 341 are summarized in Table I. Only the acoustics module scope is included in ARCH 341 course contents.

III. METHODS OF EDUCATION

A. Lectures and textbooks

In a previous study on the teaching methods of architectural acoustics, the students voted for lectures as the primary source of learning (Meriç and Çalışkan, 2013). All the lectures essentially base their framework on some specific textbooks, so that these books will be a reference for students whenever they need to consult, specifically before written exams.

In ARCH 341, the major course book is *Architectural Acoustics*, by Egan (2007), which was originally designed to be used by architecture students and is suitable for them to comprehend. It is supported by a lot of visuals and real-case/practical examples. One other reference book of the course is *Architectural Acoustics—Principles and Design*, by Mehta *et al*. (1999). The book starts with the physics of sound and covers room acoustics, sound insulation, HVAC systems, vibration isolation, and sound reinforcement systems and is appropriate for building up the framework of an architectural acoustics course either at the undergraduate or graduate level. *Architectural Acoustics* by Long (2014) is another recommended reference book, providing more mathematical background of various acoustics phenomena, a bit more advanced for architects but can be a very useful source for a group of multi-disciplinary students at the graduate level of an architectural acoustics course, or for those undergraduate students who have a special interest on the topic.

Presenting the theory of acoustics to architects at the undergraduate level is really a sensitive issue. The teaching style should balance theory and practice. Otherwise, the design-oriented students can easily lose their attention in class. Demonstrations of different physical phenomena like sound waves (can be represented with a string or a rope; a rigid connection at one end while the free end shaken to generate different wavelengths), echo, flutter echo can be easily explained through GIFs, videos, audio files, etc. The airborne and structure borne noise can be animated best by a hand-made device adopted from a music box. While playing it, holding it in air versus attaching the metal legs on the desk and detaching it by a rubber pad, or attaching only one leg while the rest sits on the rubber pad are experimental ways to highlight the significance of proper detailing in sound isolation.

On the other hand, the sound absorptive and diffusive material exhibitions are the most stimulating and fun part of the classes (Fig. 1). For this reason, making material samples available to the class is highly appreciated by the students. The feeling of the textures by hands, observing different perforation sizes and different layers of composite materials, blowing through acoustically transparent fabrics, etc., advance students' tangible knowledge. They immediately apply this information to their ongoing projects in their design studios.

B. Site visits

Although they are significant parts of the education as well as assessments tools, the library or online research on case studies—as of precedent music venues, convention canters, etc.—can never substitute visiting the sites in person and listening to the sounds of the spaces. Architecture students rely more on senses and have a better visual memory than written ones. Auditory clues complete the visual ones, and the experience is reinforced in the memory. Although the pandemic has suspended the site trips for a while, various spaces of department buildings in universities could still be utilized for experimenting. For instance, explaining the RT by clapping hands or popping balloons in different atriums of the departments is a pretty simple way of demonstrating reverberation phenomena. Sound isolation can best be experienced in a control room–practice room adjacency by asking students to shout in one room and others listen in the other one to demonstrate the performance of a sound rated window assembly (Fig. 2) or asking them to jump on the floor in one room to highlight the contribution of a floating floor system and a box-in-box construction.

FIG. 1. (Color online) Class on sound absorptive materials.

C. Design project assignment

In all covered courses under this study, implementation of a design project is an essential part of the teaching methods as well as assessments. In order to measure the acoustical performance of their design, students use various tools. Digital and hand-drawings, simulations, as well as simple calculations, are used in various degrees as explained in this section.

1. RT estimations

RT is the primary parameter in room acoustics that should be grasped well by architecture students, who will be responsible for designing speech halls, music venues, or even many different types of public spaces as of atriums. In ARCH 341, students are initially assigned to calculate RTs of a given space by a Sabine equation for the given simple rectangular space. Most of the time, their own study environment is chosen as a case, like the lecture room of the course or their architectural design studio. Given the fact that there are mostly no acoustical treatments in most of the design studios and lecture rooms of the department, the spaces are quite live and always necessitate acoustical intervention. Moreover, the students are aware of the situation due to the aural discomfort in their own working and learning spaces. For that reason, the second part of the assignment asks for a comparison of estimated RTs with the optimum ranges for the given volume and the function of the space. If the RTs of the assigned studio in its present form do not satisfy the criteria, they are asked to propose an acoustical design; treatment of room surface/s with sound absorptive material/s of their own choice in required area/s and location/s. The assignment also requires research on sound absorptive materials, which they utilize in their design proposal, and technical specifications and/or data sheets to be provided. After the proposed interventions they need to show that with the acoustical design solution the RT criteria over octave bands are met for the given space. This is mostly an individual assignment because all should learn from scratch how to do the calculation, through an excel sheet which is quite practical. In later stages of the course, more complex rooms like auditoria are assigned, to be worked sometimes in line with their third year studio project. At that point, group work and available simulation tools are allowed.

FIG. 2. (Color online) Field trip to Presidential Symphony Hall (CSO) construction site, photos from recital and control rooms, Ankara, 2019.

2. Ray diagrams

In ARCH 341, rooms for speech and rooms for music are thought in different sessions. For both functions, initial time delay gap (ITDG) is critical to be thought of in a proper way to the students. In the early stages of an auditorium design, even in the concept phase, it is not really necessary to use sophisticated room acoustics simulation software to start laying out the side walls, overhead canopies, and the suspended ceiling panels, and as such, ray diagrams are very beneficial at this point and easily comprehended by architecture students as they are pretty comfortable with drawing in two-dimensions (2D), either digitally or by hand. The term project of ARCH 341 always includes either an auditorium design or a portable stage design is asked with over stage canopy in a closed environment (like a multi-function atrium, sports hall, or design studio). To illustrate the process better, the steps of the auditorium design, as given to the students for guidance, are summarized in Table II.

The final project at the end essentially covers both room acoustics and sound insulation topics and is very helpful for students to understand the theoretical background and correlation of acoustical parameters to the architectural parameters. Students experiment with architectural input parameters including volume, room shape, surface modulations, and

TABLE II. Guide for students; acoustical design steps of an auditorium.

1	Locate your ceiling and side-rear wall panels into the hall (with surface modulations/fragmentations to provide diffusion where necessary). Illustrate the reflector coverage areas for major ceiling and wall panels, considering a sound source at the stage front. An example of selected positions (this selection will be Project specific, consult your instructor): Receiver 1 (R1): First row, center seat • Receiver 2 (R2): 6th row, 2nd seat on the right (in reference to the stage) • Receiver 3 (R3): Back row, center seat • Receiver 4 (R4): 9th row, 6th seat on the left (in reference to the stage) • Receiver 5 (R5): 1st row of the balcony, 4th seat on the left (in reference to the stage) Required surfaces for path length difference (PLD) and time delay (TD) analysis: • 4 main hall ceiling panels (as you suggested), 1 ceiling - under balcony • 2 rear/back wall panels (one for the balcony and one for the parterre) • 2 major left-right sidewall panels (4 in total)
2	For your revised/improved design of the auditorium, calculate the first order TDs (TD due to the first reflection from a specific surface - ITDG) for necessary seat/listener locations and related wall/ceiling surfaces. Note your estimated PLDs and TDs down into the tables given below.
3	Overall assess and comment on your findings: check whether your proposed design provides satisfactory listening conditions for speech halls.
4	Check if you have enough and evenly distributed reflector coverage area, check if you have any acoustical shadow. If you do so, re-orient your ceiling panels (both parterre and balcony). If you encounter probable echo formation or poor audio-environment, either re-locate your surfaces (specifically ceiling panels) and/or offer recommendations/ interventions for curing the acoustical defects for related surfaces/ areas.
5	Choose materials for interior surface finishes and provide "sound absorption coefficient data" for 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz of interior finish materials in a table. Calculate "RTs" for 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz octave bands and provide your findings as a graph-table. Be sure that RTs for indicated octave bands satisfy the optimum limits for auditoriums for speech considering the specific volume of your hall. Develop your design until you satisfy the acoustical design criteria.
6	Develop architectural details for interior surfaces/constructions together with sound isolation details including enveloping wall/ floor/ ceiling sections (1:20/ 1:10). Point details should include specifically; • details of sound reflective panels—form and dimensions (e.g., for ceilings and for walls at lower section) • details of sound diffusive elements—form and dimensions (e.g., for walls at upper section, etc.) • application details of sound absorptive elements (e.g., back/rear wall, etc.) • details of sound rated wall, ceiling, and floor (seating and stage platform) assemblies, with materials and thicknesses of different layers indicated • provide specifications and/or illustrations of your selected auditorium seat and number of seats of your hall.

materials. The overall workload of this term project is 40 h including class hours and preparation at home. Some examples of term project outcomes from different semesters are presented in Fig. 3.

3. Simulations

Acoustical simulations by specialized software, such as ODEON (2008) in our case, is certainly very helpful to demonstrate room acoustics, especially for the digitally-oriented student of this era. The problem with undergraduate students is that the number of students in architecture schools that are taking the must course in their third year mostly is around 80 each semester. Due to the limited number of licenses for experimenting with the software, acoustical simulations are utilized only at graduate level course by a fewer and manageable number of students.

In BS 575, students are asked to test their design through computer simulation by a number of acoustical parameters that are critical to acoustical design. The main function specified in the architectural program is concert use. Each semester, the project is slightly revised. One example is the assignment of a music hall where symphonic concerts of the romantic era and baroque music are to be performed. Multifunctional use is an extra asset if it can be addressed in the design. In such a case, if multifunctional use is also opted, functions made available by the designer should be specified. The targeted capacity of the hall is for an audience size of 1000, 2000, or 1500 people and for an orchestra size of 60 or 80 (audience and orchestra size are varied each semester). Students are free to comply with this requirement with or without balcony. The form of the space is left to the designer's choice. However, both the form and dimensions of the hall are expected to be suited for the function(s) chosen. The project report is to include architectural design (plans and sections) and simulation results in graphical form. The material list must also be supplied along with location information on source and receiver locations. Grid responses should be provided for acoustical parameters (ISO, 2009) as of RT (T30), early decay time (EDT), clarity (C80), lateral energy fraction (LF), A-weighted sound pressure level (SPLA), and speech transmission index (STI) for all possible functions/architectural/acoustical program considered in the design. An overall assessment of the design is required at the end of the report. One of the first project applications using ODEON, as the department owned an educational version in 2003, is experimentation with different hall shapes including shoe-box, fan shape and horseshoe shaped halls. Students had the chance to compare their acoustical parameter results over distribution maps and discuss the pros and cons of each form. See Fig. 4. The experience was later presented in a national conference and was published in Proceeding's book (Arslan *et al.*, 2004).

D. Laboratory tests

In the BS 575 graduate course, lectures on concepts like sound absorption coefficients of materials are supplemented with experiments in a standing wave tube. Formation of standing waves along the length of the tube is demonstrated with basic elements of a measurement system made up of an oscilloscope, sine wave generator, and an amplifier to measure standing wave ratios for several samples of absorptive

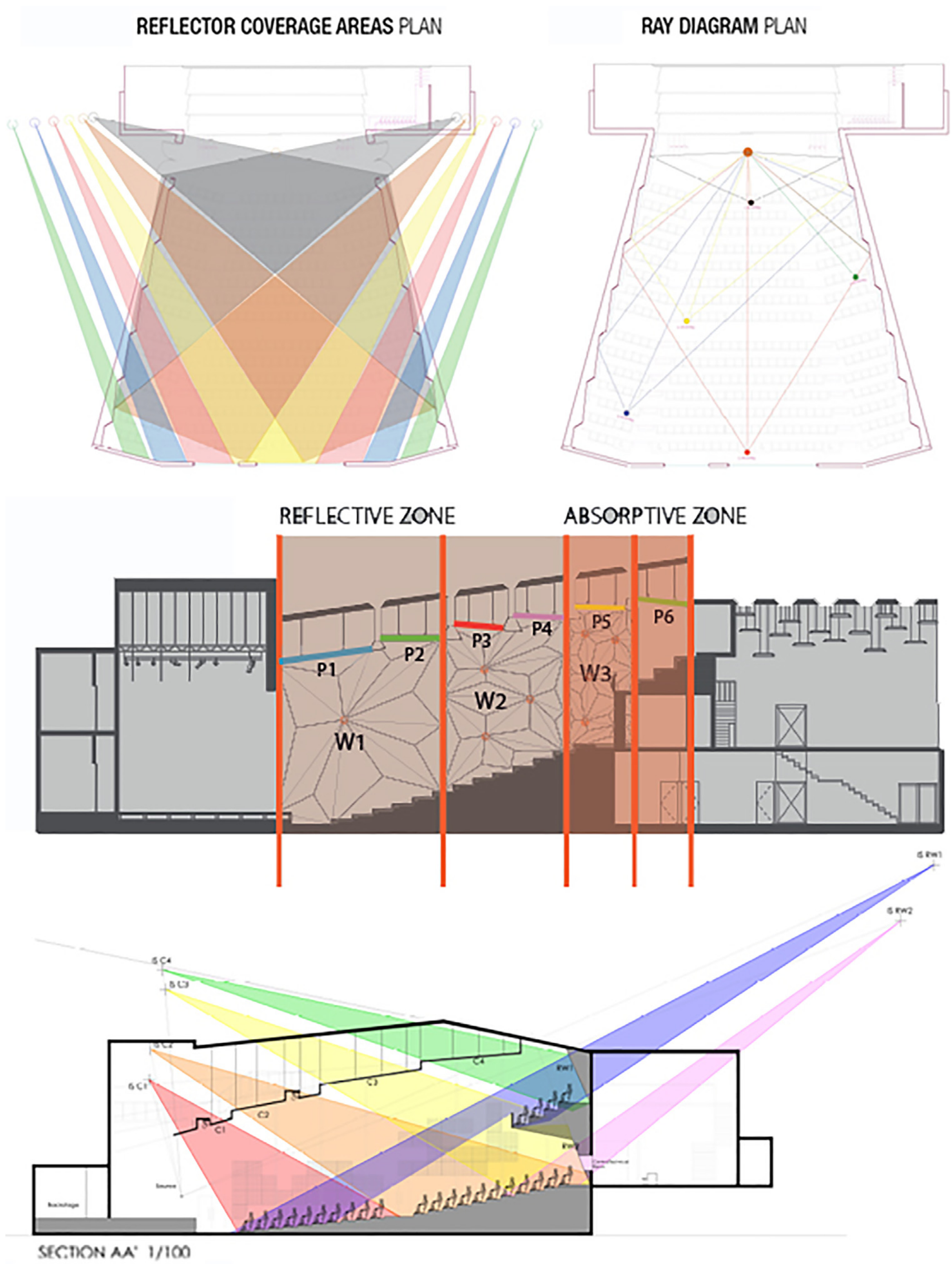

FIG. 3. (Color online) Plan and section views, PLD, and reflector coverage analysis of selected student projects.

materials placed in the sample holder of the set up at one end of the tube. A traveling microphone within the tube is provided to locate maxima (antinodes) and minima (node) of harmonic standing waves to check the frequency values on the digital counter of a signal generator. Amplitudes in terms of voltage at these two points are measured on the oscilloscope screen to form a standing wave ratio. The corresponding sound absorption coefficients specific to the sample and its mounting type, i.e., with or without airspace behind the sample can be calculated accordingly. This way students have hands-on experience with the measurement of a normal-incident sound absorption coefficient, which is far more long-lasting in their memories than written information in text books or laboratory test reports. See Fig. 5.

E. Applied material research

As previously elaborated, experience with materials is very valuable for architecture students. The form, texture, and feeling of materials are tangible aspects of architecture, which eventually raise student interest in the topic. During one semester, as part of the term project of ARCH 341, students are assigned to design and produce acoustical panels to be applied to their own architectural design studios. The motivation behind the assignment is that the present design studios are highly reverberant, and both the students and the instructors complain about the aural discomfort within the studios. The situation is even more problematic for those studios that are shared by two different sections; meaning

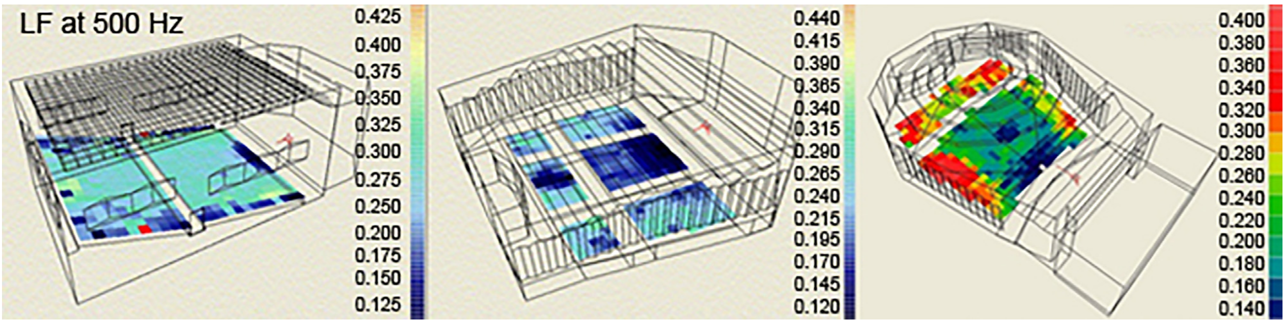

FIG. 4. (Color online) BS 575, one of the first project applications using ODEON; students experimenting with different hall shapes (Arslan *et al.*, 2004).

two different instructors talking (or discussing with students) simultaneously within the same indoor space at different corners of the room. So, in order to quantify this real case problem, students are initially challenged to estimate the RT of their studios for its current condition. Later, they are asked to propose an acoustical design for the treatment of room surface/s with sound absorptive materials of their own design. The developed sound absorptive or diffusive panel sizes are required to be a minimum of 120 cm × 60 cm. The choice of base material, infill, and claddings are critical in sound absorptive material design, so the students are asked to receive critiques from their instructors during the process before they finally manufacture the products. The final product should also include the proposal for its application (hanging) details, either to be hanged on the ceiling or applied over the walls. The students, in groups of two or three, are asked to produce at least four of these panels for submission. All the panels produced by in total 75 students from two sections are collected and proper ones are selected to be applied. Later, those panels are hung over walls and ceilings as proposed by the students in two selected studios (Fig. 6). The assignment was planned to be repeated in the following semesters in order to improve, one by one, every problematic studio of the department. However, the pandemic conditions have currently suspended progress of the project for a while.

One interesting outcome of the project is that a group of students utilized cardboard cups collected from coffee shops to reuse the waste material. In order to control long RTs and improve the intelligibility of speech within the studio, originally a two-layered panel system was developed. The collected cardboard cups differing in size were placed in different orientations as a front layer. This layer is backed by 25-mm thick 90 kg/m^3 mineral wool providing structural stability as well as sound absorption. After the project submission in ARCH 341, the students further developed their panel system during their final semester before graduation. In place of mineral wool as a backing absorptive layer, biodegradable and recycled materials are investigated. As a result of this research, the coffee and tea residues are processed into coffee and tea panels (Fig. 7). Sound absorption coefficients of the produced material samples are tested by Kundt tube and the potentials of re-using such biomaterials for acoustic purposes are discussed in a recent acoustics congress (Sel *et al.*, 2021). Being able to present their research from undergraduate studies at an international conference and getting feedback from the experts is quite a unique experience for the students.

FIG. 5. (Color online) Standing wave tube used in BS 575 course.

F. Assessment

In BS 575, the final project output is a concert hall design supported by simulation studies as discussed previously. This accounts for 40% of the overall grade. BS 576 students are asked to prepare a written report on a specific subject related to the concepts taught in the course as a term paper. Focusing on sound insulation aspects, including sound-rated floor and wall types, sound insulation details, sound-rated window and door details etc., students analyze a project that is constructed by necessary research on the project documents and by field trips if possible. The study should also be supported by reviewing national and international acoustical design criteria/standards/codes or regulations that can be applied to that specific building typology. Some example term paper titles proposed by students are: "Noise and Acoustic Concerns in Healthcare: case study of Bağcılar Hospital in İstanbul," "Elementary School for Children with Leukemia; study on its acoustical conditions," "Measurement of Sound Power Level of a Farmer's Market Place in Ankara by ISO 8297." The term paper makes up 50% of the overall grade. The rest of the grading includes homework, midterm, and final exams. In ARCH 341, 35% of the final grade is the term project, different examples of which are detailed in this paper, 20% of the overall grade includes case study research, field examinations, and other short assignments as of RT calculations, 35%

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FIG. 6. (Color online) One of the studios before acoustical panel applications (on the top left corner) and after the panels designed and produced by third year undergraduate students.

includes open notebook midterm and final exam, and the last 10% is in-class participation.

IV. DISCUSSION

The methods of teaching described in detail within this paper cover one undergraduate level and two graduate level courses from two leading universities in Turkey. The medium of instruction at both universities is English. While there is a growing body of full-time and exchange students coming from 73 countries, currently almost 10% of the students at Bilkent University are international. The undergraduate course taught at Bilkent University, ARCH 341—Architectural Lighting and Acoustics, is a must course available in the Fall semester and in the Spring semester, it is followed up with ARCH 342—Environmental Technology, which covers the topics in relation to passive energy design, active systems (HVAC), electrical systems, fire safety in buildings, etc. These two courses (each with 5 ECTS credits) are a few of the technical courses taught within the four-year condensed architectural curriculum of Bilkent University. The Bachelor's degree is awarded to students who successfully complete 240 ECTS. The situation is similar to other Turkish universities.

Within a variety of disciplines affecting architectural design, promoting student awareness of acoustical comfort and noise control without exhausting or overloading information in a half semester is the main challenge. If the student's attention can be secured and their interests in the topic can be captured, they apply the information eagerly in their design studios. Some students even pursue their graduate education in acoustics and get more expertise in the field. This is around 3%–5% of the total students whom graduate from the department of architecture each year. On the other hand, approximately 2% of the students withdraw from the course when they take the class for the first time. Eventually, they all need to complete the course with a passing grade in order to be able to graduate from the department.

The best way of assessing the efficiency of teaching methods that are developed over the years and listed in this paper is student feedback (covering the years between 2013 and 2022). In relation to ARCH 341, one of the most common positive responses is the student's appreciation of the instructor's effort for them to learn by bringing a variety of materials and equipment (like sound level meter) to class, which are used in the field of acoustics. They state that this helps not only theoretically but also practically because they can be involved in the contents of the course. And during the high pandemic days, the online classes are vastly criticized for the deficiency of such hands-on experience with tools and materials.

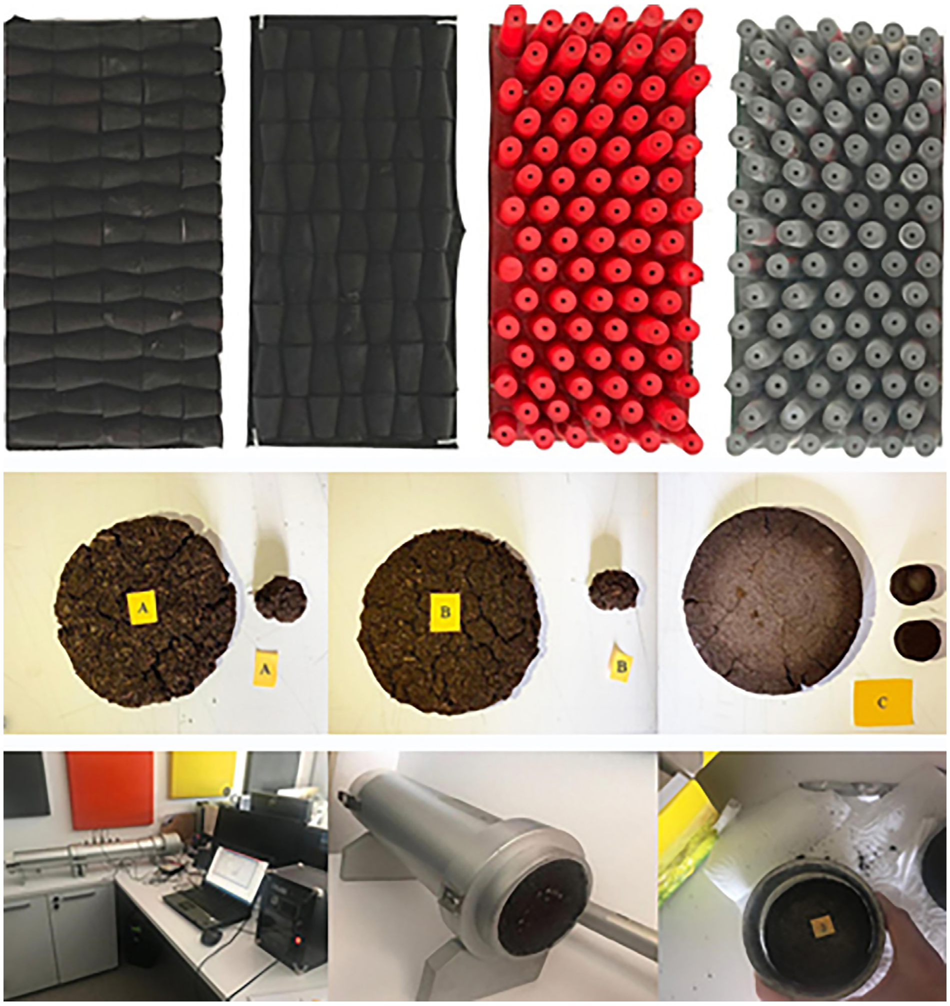

FIG. 7. (Color online) Different panel arrangements of cardboards (on top), photographs of coffee and tea waste panel samples (in the middle), measurement set-up by Kundt Tube (at the bottom).

Another positive feedback from the students is professional life examples from the practice experience of the instructor that are discussed in classes. Undergraduate students also appreciate it greatly when the teaching assistants, who are our graduate students, use a couple of the allocated class hours to present their on-going research with a focus on architectural acoustics.

At the end of semester course evaluations, regarding ARCH 341, students state that both lighting and acoustics are two important elements in architecture, so it is important to have at least a basic knowledge about them to further develop their projects. However, they still recommend that one semester covering both lighting and acoustics is too much of a workload, and thus these courses should be split and each should be given a complete one semester with more time to go into the details.

The graduate level courses discussed in this paper, BS 575 and BS 576, are those offered at METU, in the Fall and Spring semesters, respectively. BS 575 and BS 576 courses are opened only if a minimum of three students register for the course. Both undergraduate and graduate students can take these courses. However, most of the time, graduate level students enroll to the 5XX coded courses. In order to assess the role of acoustics courses in architectural education, in 2013, a questionnaire was held by Meriç and Çalışkan surveying 25 participants who were former students that took the graduate acoustics courses of BS 575 and/or BS 576. Some of the participants at the time were still continuing their graduate education and others were working professionals. Some student responses to be mentioned in relation to this paper are as follows: the strongest motivation of undergraduate students who took these courses is their interest in subjects related to acoustics. Five of the undergraduate students also believed that course content would make a contribution to their professional life. Most of the participants chose lectures as the most beneficial method that affected their learning process and placed this group at the first rank. One can speculate whether this outcome is related to the teaching performance of the course instructor. The least effective method is chosen as exams. Case studies and simulations are placed in the second rank of the most effective teaching methods. Students assess simulation as a useful tool, as they state that they get the opportunity to use their knowledge parallel with the design process and see the possible conclusions of their choices. To the amazement of instructors, apart from simulations, these groups of students could easily relate room shape and dimensions to issues covered in small-room acoustics for hard-walled rectangular rooms where they are quick to calculate resonance frequencies and illustrate room modes by simple sketches for rectangular rooms. Other teaching methods including guided readings, independent study/research, and assignment/term paper, are ranked in between second and the least rated method of teaching. This survey demonstrates the effectiveness of several methods of instruction on architects-to-be in grasping theoretical aspects as well as practical issues of architectural acoustics.

V. CONCLUDING REMARKS

Like an orchestra maestro being responsible for the sound of every single instrument, an architect is responsible for many factors that have to work together for the harmony and functionality of architectural spaces, including light and sound. This paper focuses on the understanding of sound in architecture by future architects in their undergraduate and graduate education. The courses described in this paper and selected tools and projects are not specifically for those students who will indeed pursue their carrier as an acoustician, although they still may. Rather, the curricula are set to provide a basic knowledge of acoustics, while evoking their interest and awareness on the significance of the topic without getting too much into the details of regulations and codes. For keeping the interest of students alive, it is very critical to set a proper balance between theory and practice, tangible and intangible parts of acoustics in their education. On the other hand, design and architecture departments worldwide may not all have sophisticated tools for measurements or demonstrations of architectural acoustics concepts. Thus, the study also highlights some techniques and approaches that can be employed in architectural acoustics education without advanced technology, even with basic and limited resources, simply by active inclusion of the design background and creative thinking of architecture students in this applied research area.

Arslan, S., Sü, Z., and Çalışkan, M. (**2004**). "Contribution of the computer simulation to the process of design in the courses of architectural acoustics: A study of 500 seated concert hall," in *Proceedings of 7th National Acoustics Congress (TAKDER)*, November 17–19, Cappadocia, Nevşehir, Turkey, pp.129–137.

Busch-Vishniac, I. J., and West, J. E. (**2007**). "Acoustics courses at the undergraduate level: How can we attract more students?," Acoust. Today. **3**, 28–36.

Egan, D. (**2007**). *Architectural Acoustics* (J. Ross Publishing, Fort Lauderdale, FL).

ISO (**2009**). ISO 3382-1R, "Acoustics—Measurement of room acoustic parameters—Part 1: Performance spaces" (International Organization for Standardization, Geneva, Switzerland).

Kang, J. (**2008**). "Computer tools for architectural acoustics education," J. Acoust. Soc. Am. **123**(5), 3653–3654.

Kitapçı, K. (**2019**). "Room acoustics education in interior architecture programs: A course structure proposal," in *Proceedings of INTER-NOISE*, June 16–19, Madrid, Spain.

Llorca, J., Redondo, E., Alba, J., and Mendoz, H. (**2018**). "Generation of architectural designs using soundscapes: First findings," in *Proceedings of DAGA*, March 19–22, Munich, Germany, pp. 1046–1048.

Llorca-Bofí, J., Brell-Cockan, S., and Vorländer, M. (**2020**). "Pedagogical approaches to acoustics for architecture students," in *Proceedings of DAGA*, March 16–19, Hannover, Germany, pp. 539–541.

Long, M. (**2014**). *Architectural Acoustics*, 2nd ed. (Elsevier, New York).

Mehta, M., Johnson, J., and Rocafort, J. (**1999**). *Architectural Acoustics—Principles and Design* (Prentice-Hall, Englewood Cliffs, NJ).

Meriç, I., and Çalışkan, M. (**2013**). "Acoustics education for architects: Developing a base of knowledge for professional experience," in *Proceedings of INTER-NOISE*, September 15–18, Innsbruck, Austria.

Milo, A. (**2020**). "The acoustic designer: Joining soundscape and architectural acoustics in architectural design education," Build. Acoust. **27**(2), 83–112.

ODEON (**2008**). "Room acoustics program version 8.5 user manual industrial, auditorium and combined editions," http://www.odeon.dk (Last viewed March 2022).

Schröder, D., and Vorländer, M. (**2011**). "Raven: A real-time framework for the auralization of interactive virtual environments," in *Proceedings of Forum Acusticum*, June 27–July 1, Aalborg, Denmark, pp. 1541–1546.

Sel, E., Düzova, İ., Şireli, A. E., Yazıcı, B., and Sü Gül, Z. (**2021**). "Reuse of coffee and tea waste for acoustical panel applications in architectural design studios," in *Proceedings of INTER-NOISE*, August 1–5, Washington, DC (Virtual).

Sheridan, T., and Lengen, K. V. (**2003**). "Hearing architecture: Exploring and designing the aural environment," J. Arch. Edu. **57**, 37–44.

Sygulska, A. (**2021**). "Teaching acoustics to students of architecture," World Trans. Eng. Tech. Edu. **19**(1), 113–118.

Tamer Beyazıt, N., Hohman, A., and Reder, R. (**2012**). "Aural architecture or acoustic architect—How to teach acoustics to architecture students," in *Proceedings of INTER-NOISE*, August 19–22, New York, pp. 3037–3048.

The Turkish Regulation on Noise Control for Buildings (**2018**). https://www.resmigazete.gov.tr/eskiler/2017/05/20170531-7.htm

Yüksel Can, Z., Maffei, L., Semidor, C., and Kang, J. (**2009**). "Experiences in noise control education in architecture," in *Proceedings of INTER-NOISE 2009*, August 23–26, Ottawa, Canada, pp.1051–1060.