Advances in diffusive surface design using 3D architectural parametric modeling programs

PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Advances in diffusive surface design using 3D architectural parametric modelling programs

Louena SHTREPI

Politecnico di Torino, Italy

ABSTRACT

Diffusive surfaces need to be optimally designed for both acoustic performance and aesthetic values. These aspects are at the heart of the design workflow and should respond to the requirements of both architects and acousticians. Advances in parametric modelling through digital tools have led to the integration of performance investigations and architectural design process. Moreover, parametric modeling software are also useful tools for manufacturing. Indeed, they can reduce the production time as they can easily be integrated inside the manufacturing process.

Although, it is more than a decade that the standard ISO 17497:2004 has proposed the scattering and diffusion coefficients measurements, further work is needed in order to increase designers' awareness on diffusive surface design through simple design rules and approaches.

This research goes through three steps. First, it investigates the diffusive surface properties databases in order to extrapolate basic geometric guidelines for diffusive surface optimization. Second, it analyses a series of case-studies that apply the parametric modeling to the design of diffusive surfaces. Finally, it suggests a design process for diffusive surfaces by integrating parametric models and acoustic simulation aiming to provide architects and designers with rapid visual and acoustic feedback at a preliminary stage of their design.

Keywords: Sound, Simulation, Diffusers, Scattering, Parametric modelling

1. INTRODUCTION

Diffusive surfaces are essential elements that determine the acoustic quality in performance spaces in terms of first-order reflections control (1, 2). They are used also in other environments, such as classrooms or outdoor spaces, to increase speech intelligibility (3) and reduce sound noise levels (4, 5). Diffusers have continuously challenged acousticians' abilities in performance and proper use within different environments; they have also tackled the creativity of designers, as these surfaces strongly determine the visual outcome of the space (6). Only a few documented cases benefited from an integrated approach of both these two aspects (7-10). A parametric design thinking (PDT) (11) results appropriate and necessary to deal with the complexity of these surfaces. This approach allows for a greater level of detail and differentiation for the entire space as well as for each single building component. Therefore, further research is needed to highlight the benefits of PDT application to the complexity of the design of diffusive surfaces, in order to obtain a richer design and meet the acoustic performance requirements. As it is reported in Wortmann and Tunçer (12), the strength of PDT does not lie in generating many design variants, but rather in realizing highly specific, differentiated, rule-based designs. The design process has increased its scale increasing the number of professionals that include architects, consultants and contractors. Therefore, it is required to practice PDT for a more efficient design process, which highlights the need for software and programming language that allow for data exchange. Based on this approach, this work aims to highlight the new perspectives of the diffusive surface design that integrate computational and materialization tools.

Acoustic performance requirements are related to the scattering coefficient and the diffusion coefficient (13), introduced in the standard family ISO 17497 (14, 15) which has eased the construction of reliable database of scattering and diffusion coefficients (6). These data are not only necessary to compare different diffusers but are also adoptable as input data for acoustic simulations in the preliminary conceptual or verification phase of the project (16-18). However, these measurements are usually costly and time-consuming; therefore, they are mostly limited to research and high budget design projects.

To overcome such limits, accurate prediction models have been validated (19-21), enabling to optimize diffusers and control their properties at different incident angles (22). The most common example of optimization concerns the Schroeder diffusors. Cox (23) showed the optimization process through iterative boundary element method (BEM) based simulations. Other works showed the application of Finite Elements Methods (FEM) and Finite Difference Time Domain (FDTD) for multi-objective optimization starting from the design of the sonic crystal sound diffuser (SCD) effective at low frequencies (24) and sound phase diffusers (25). Orlowski (26) and Cox (27) showed cases of curved diffusors optimization, and profiles of optimum diffusers were suggested in Takahashi (28). However, the high computational cost of these methods makes them unadoptable in the early design stages, when a high number of solutions are rapidly produced and discarded. Therefore, rapidity is chosen over accuracy allowing the assessment of non-standardized solutions, which require an exchange of information also with the fabrication process aspects. Acoustic performance as a key design factor of the built environment has been pointed out in recent studies (29). Reinhardt et al. (8) investigated the design affordances of acoustically efficient patterns for sound scattering through computational design and robotic fabrication. Peters and Olesen (7) used rapid prototyping for an easier fabrication of scattering surfaces samples based on hexagonal elements with varied depth and width. The data obtained by measurements according to ISO 17497-1 method were used to inform the parametric design tools for the performance optimization. Further, visionary explorations suggest to deploy robots to evaluate the designs of diffusive surfaces and directly react on the measured results during the fabrication process within a given design framework, i.e. a process of architectural and acoustic tuning (29).

All the presented case studies imply a workflow that includes development of computational design tools, geometry generation, fabrication of test surfaces, measurement of acoustic performance, and the integration of these data into a generative tool (7-10). This approach is subject to continuous evolution and requires a customization of existing software through computer-programming (12). As highlighted by Whitehead (30) most designers already think programmatically, but since they are lacking the time and the inclination to learn programming skills, they cannot express or explore these patterns of thought. Therefore, a new professional figure might be needed to embrace design and acoustic knowledge in order to generate valid solutions from both aesthetical and acoustic point of view with smaller effort.

This work aims to give simple geometrical guidelines for the optimization of diffusers performance based on a literature review. Second, it analyses four case-studies that apply PDT to diffusive surfaces design, in order to identify the workflows of the optimization process. Finally, it suggests a design process for diffusive surfaces by integrating parametric models and acoustic simulation aiming to provide architects and designers with rapid visual and acoustic feedback at a preliminary design stage.

2. DIFFUSERS OPTIMIZATION

The acoustical characterization of diffusive surfaces relies on two standards: ISO 17497-1:2004 (14) defines the measurement of the random-incidence scattering coefficient in diffuse field as the ratio of the non-specularly reflected sound energy to the total reflected energy; ISO 17497-2:2012 (15) defines the measurement of the directional diffusion coefficient in free-field as a measure of diffusers quality. Both these coefficients are frequency dependent single numbers and all the data obtained from these measurements makes easier the comparison between different surface treatments (13). Diffusers performance optimization aims to maximize both these parameters; to achieve this goal, know-how on the acoustic effects of a large number of geometrical variables is necessary. This knowledge can be based both on a systematic analysis of the literature and an *ad hoc* optimization when a fabrication system and a measurement set-up can be easily integrated. Furthermore, a computational process can be integrated in the design process to exploit the potential of parametric modelling of different topologies and deduce design rules.

2.1 Diffusion coefficient optimization

A good diffuser has the ability to uniformly scatter in all directions, rather than just move energy away from the specular angles (22). To this aim, curved diffusive surfaces can easily achieve higher uniformity of the polar distribution of the scattered energy. As shown in Cox and D'Antonio (6), geometrical elements organized in arrays and modulated, for example, as Schroeder diffusers are likely to generate a good spatial distribution. Therefore, an asymmetrical base shape as well as the reduction of periodicity are preferred.

Two important studies (31, 32) have presented deep-subwavelength diffusing surfaces based on acoustic metamaterials, namely metadiffusers. They have redesigned the Schroeder diffusers based on the concept of an acoustic metasurface in order to obtain surfaces with broadband uniform spatially dependent reflection coefficients optimization. This methodology has led to ultrathin diffusers named broadband metadiffuser only 3 cm thick, while conventional solutions are 69 cm thick, effective at 250Hz. However, they are still at an embryonic stage from the real-world application perspective.

Table 1 – Summary of the design rules for diffusive acoustic surfaces based on the design at the level of the single scattering elements

Variable	Pattern	Design rule	Effectiveness on scattering and diffusion	Ref.
Size	Pyramids	Increased height	Increase at Low and Mid frequencies	(33)
	Extruded profiles (Schroeder diffusers)	Increased height	Increase at Low and Mid frequencies	(34)
	3D diffusers	Height > 20 cm	Increase at 500-3150Hz.	(35)
	Rib structures	Height > 18 cm and width of 10 cm	Increase at < 500Hz	(36)
		Use of different heights in the same panel	Increase at 125-4000 Hz (smoother curve of the frequency dependent scattering)	
	Periodic type diffusers based on rib structures	Square section (5cm, 10cm and 22cm)	Increase at Low and Mid frequencies	(3)
	Fractal order	Use of different sizes simultaneously	Broadband; Higher uniformity in the polar distribution	(37)
Configuration	Random array of cubes (20cm)	Randomization	Increase at 500-1000Hz and at high frequencies, starting from 3.15 kHz	(36, 38, 39)
	Penrose configuration.	Aperiodic	Increase at 500-1000Hz	(37)
Coverage density	Cubes of 20cm	Coverage density around 50%.	Broadband	(36)
	Hemispheres	Coverage density around 57 - 58 %	Broadband	(38)
	1D, 2D and 3D diffusers	38%, 46% and 57%, respectively.	Broadband	(35)
Distance	Structures of 2.5 cm	20 cm and 40 cm	Increase at 500-2000Hz	(37)
	Periodic rectangular ribs of 4.7 cm	15.1 cm and 30.2cm	Decrease of the scattering values in the frequency range 500-3150Hz	(21)
Profile shape	periodical profiles	Rectangular, triangular and semicircular profiles	High frequencies are improved by triangular and semicircular shapes; mid frequencies benefit by the rectangular profile	(40)
	Wave	Sine sweep profile	Increase High frequencies	(41)
	Extruded triangles	Triangular profile	only for specific generator angles. ($30° < \chi < 45°$)	(6)
	Alternation of concave and convex surfaces	Oriented orthogonal to each other	Broadband	(42)
	Prismatic elements	Prismatic elements	Lead to higher scattering values compared to pyramids or plates of the same dimensions	(37)
	Deep triangular prisms	Asymmetric profile	Broadband	(43)

2.2 Scattering coefficient optimization

Table 1 shows a summary of the design rules that can be deduced form the current available literature. This data can be useful at the conceptual phase of the design workflow.

The size of the scattering elements is the first design aspect that can be controlled. The analytical model in (13), that is $f=c/2a$ or $f=c/2h$, shows a linear relation between the frequency and the size (a=width or length, and h=height) of the scattering elements and provides the frequency at which scattering becomes effective; for smaller frequencies only the specular mode is reflected by the profile. However, according to ISO 17497-1 (14), the height of the diffusive elements is restricted to a maximum of 1/16 of the diameter of the measurement rotating table (≈24cm).

3. EVALUATION OF THE DIFFUSIVE SURFACES

The above summary shows that the actual know-how on geometrical parameters impacting on acoustical performance relies on a great number of measurements. The retrieved database could be used to test the accuracy and the reliability of prediction models to further improve the entire workflow of a design process.

3.1 Prediction of Sound Scattering and Diffusion

Different theoretical models based on FEM and BEM methods have been used to analyze the sound waves reflected by a diffusive surface (19). Usually, these methods require advanced theoretical knowledge and very long calculation times which prevent an immediate feedback. These drawbacks leave designers apart from the acoustical performative investigation of the surfaces they design.

Acoustic performance of single surfaces can be integrated into architectural design workflows (7-10) by adopting parametric modeling and computer programming techniques. The most preferred environments are usually visual programming environments, such as Grasshopper: it allows the users to drag-and-drop predefined operations and connect them into a directed, acyclic graph (44). Acoustic analysis within Grasshopper can be made through the plug in Pachyderm Acoustics (45): this software package integration allows for the development and investigation of performance driven geometries at a higher complexity level. A process rationalization leads to a series of mutually informed computational clusters and enables a completely digital workflow from the concept phase to manufacturing (46).

3.2 Fabrication

The prototyping phase as well as the final output of a design workflow are strongly influenced by materialization concepts (47). As shown in Gursoy and Ozkar (48), computational formalisms aim to include material aspects of design additional to the visual ones. This approach can be applied also to the integration of the acoustical performance.

The versatility and adaptability of different fabrication techniques such as 3D printers, CNC milling machines, and industrial robots have enabled the exploration of new building techniques as well as the generation of very complex surfaces (7-10). Also the fabrication aspects are subject to continuous research since there are still limitations regarding the samples size in 3D printed samples and the optimization of tool paths in CNC manufacturing. The adoption of robots enables the exploration of complex topologies with higher precision, even for scaled surfaces (47). The design rules should consider these limitations very carefully since it determines the product costs.

4. CASE STUDIES

The approaches introduced below propose the development and testing of a large number of alternatives integrating the acoustic performance of diffusive surfaces as one of the design criteria.

These approaches allow to shift from a validation procedure done at the end of the design process to a conceptual design tool that allows acoustics performance to become part of the conceptual architectural design strategy (7).

4.1 Case study 1: Hexagonal structures

The design workflow proposed by Peters and Olesen (7), shows how the possibility to test and measure a large number of cases would allow the computational tools to learn and have higher predictability power for future design. Machine learning techniques could help to explore extreme design solutions to overcome the current measurement limitations. This workflow relies on the following steps (Figure 1):

(i) Three different topologies have been generated in a first conceptual phase and architectural design parameters are specified. (ii) A hexagonal diffusing structures is chosen for the further steps using the digital tools (a Microstation Visual Basic) and is parametrically designed based on simple rules related to well depth and well width. (iii) Six options at 1:10 scale are fabricated by using a 2Corps 3D printer and generating circular samples useful for the next step. (iv) The scattering coefficient for all these surfaces is measured in agreement with the ISO 17497-1. This is the most challenging step, since it is affected by a large number of uncertainty factors. However, it allows to obtain the acoustic effect of the topological parameters, that is, of well depth on the frequency distribution of scattering values and well width on its magnitude. These are considered as the acoustic design aims. (v) The collected data are used as input for the design tools and allow to explore further alternatives without necessarily performing the measurement phase.

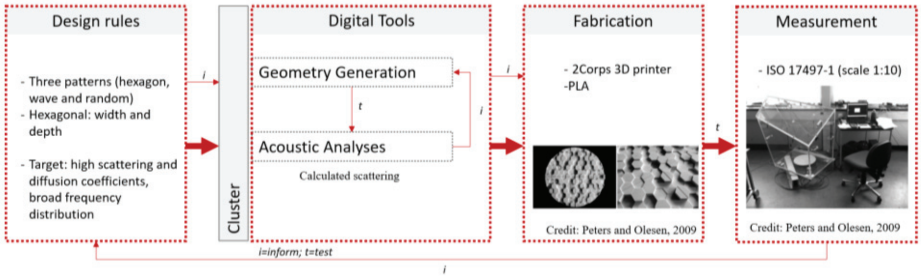

Figure 1 – Case study 1 workflow: design rules, digital tool, fabrication and measurements details.

4.2 Case study 2: Micro-Design structures

Here the conceptual framework and pattern language available for acoustic scattering are extended by highly flexible robotic fabrication in a search for "acoustic effects of complex architectural geometries" (8). The iterative design process consists of the following steps (Figure 2):

(i) First, architectural design parameters are set, along with the acoustic design aims (e.g. scattering coefficient spectrum). Parametric hexagonal and curvilinear splines are used to obtain two different design alternatives through the parametric digital tool GH Grasshopper (a plug-in of McNeel Rhino visual scripting environment). Design parameters for hexagonal splines are surface angles, height, depth and directionality of the elements; in curvilinear splines, a variable number (up to 9) of attractor points are used to orient and control the depth of the created isocurves. (ii) The computational design of specific surface micro-geometries is performed. The toolpath of the robot is adjusted in KUKA|prc, which is a Rhino McNeel plug-in for fabrication. (iii) A CNC milling and a 7-axis robotic fabrication of physical scale model test samples is made in the form of circular samples useful for the next step. The samples are designed with 310 mm diameter and 19 mm depth and prototyped in subtractive cutting processes in XPS Styrofoam and wood. (iv) Acoustic measurements in a 1:10 scaled reverberation room and analysis of sample performance are implemented based on ISO 17497-1. (v) Finally, design refinement is made, and further iterations are performed if necessary. At this point the angle of the sound reflection is linked to the robotic toolpath, thereby controlling the depth of the sample structure in order to obtain the desired reflection through the reverse process.

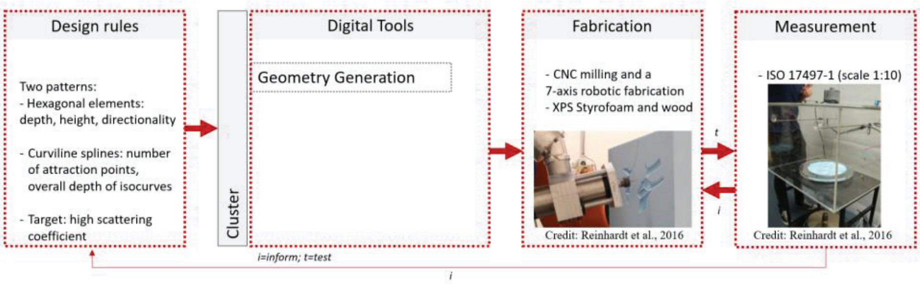

Figure 2 – Case study 2 workflow: design rules, digital tool, fabrication and measurements details.

4.3 Case study 3: Milled wood panels - students workshop

New simulation methods made possible for architects to calculate and digitally visualize acoustic properties and how geometric variations affect its performance (9). The entire workflow is first digitally tested; only the final, optimized result is fabricated. This is as an attempt to establish a design method that incorporates simulation of acoustic performance and robotic fabrication of milled wood panels, based on the following steps (Figure 3):

(i) Design geometric specifications are left open to each student in order to explore the limits of the design process on creativity and cognitive process. (ii) This case study groups into a computational design system four clusters related to (a) the Path Generation, where the user directly manipulates the curve-based milling paths and informs the next cluster; b) Geometry Generation cluster, where the user performs a subtractive process of removing material and graphically visualizes the resulting milling simulation. The geometries are generated using parametric modelling based on Rhino and Grasshoper tools; c) the geometric shape is tested in the Acoustic Analyses cluster through simulations with Pachyderm Acoustics and the performance is compared to the chosen target (e.g. high scattering coefficient). This step informs the first cluster creating new milling paths and after the second cluster step it also generates new optimized shapes; d) the last cluster is named Robotic Simulation and uses the KUKAprc package to simulate the fabrication process. An optimization of the fabrication process can be performed at this step and inform the first cluster. The simulations hold the potential of acting as valuable feedback for the next iteration of re-designed and increasingly informed curve geometry. (iii) The optimized solutions are fabricated through a KUKA KR300R2500 with a 7.5KW CNC spindle mounted as its end effector.

The authors have highlighted some of the of the digital tools limitations that made impossible a continuous data flow between the four clusters. However, they noted that an immediate visual feedback was extremely helpful at the different levels of the workflow.

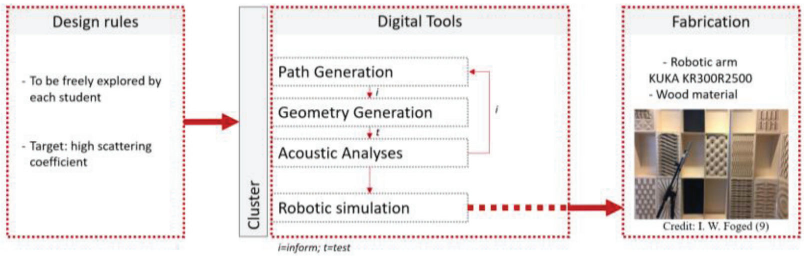

Figure 3 – Case study 3 workflow: design rules, digital tool, and fabrication details.

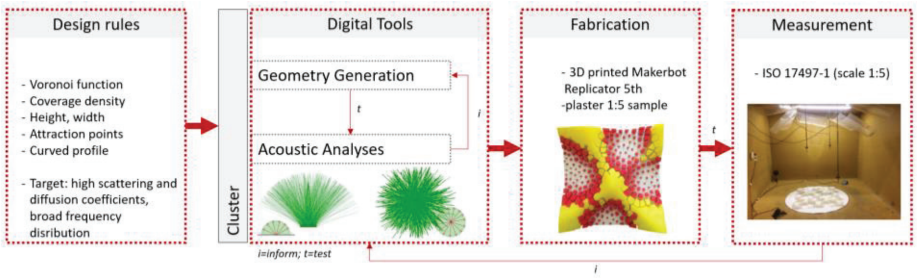

Figure 4 – Case study 4 workflow: design rules, digital tool, fabrication and measurements details.

4.4 Case study 4: Voronoi structure

This case study aimed to implement a feasible method with a rapid visual feedback that could help the designer at the conceptual stage of the design workflow (10). The acoustic performance at this phase is mainly digitally tested by limiting the prototyping costs. The following steps are suggested (Figure 4):

(i) Different geometric design rules are used based on those introduced here in Section 2 in order to maximize the scattering coefficient and improve the uniformity of the reflections spatial distribution The geometry of the bases is a Voronoi function that allowed for a randomized structure of the elements. The coverage density, height and dimension of the elements are varied using four attraction points. Further, the entire surface is intersected with a curved profile for a more spatial reflection distribution uniformity. (ii) A Computational Design System is built with two clusters, that are the Geometry Generation and Acoustic Analyses clusters. The first cluster uses Rhino and Grasshopper for the parametric modelling. The second cluster uses an *ad hoc* script integrated in the first cluster and informs it on the acoustic performance based on a first qualitative approach that is later integrated with a quantitative one that uses Pachyderm Acoustics. (iii) The optimized surface is then 3D printed through a Makerbot Replicator 5th generation using PLA. Since the 3D printing required a very long production time, a plaster 1:5 model of the complete sample was produced for acoustic measurements. (iv) The surface is characterized from the scattering coefficient point of view based on ISO 17497-1 measurement approach. The data are used to inform the Geometry Generation cluster.

5. CONCLUSIONS

This paper has analyzed different studies, which have investigated the diffusive surface based on the ISO 17497-1 standard. The aim was to analyze the geometrical rules tested in each experiment in order to give useful and simple guidelines to designers for the optimization of diffusers performance. Further aspects could be investigated through BEM or FEM simulations in a more systematic way in future work. Four case studies related to the design workflow of diffusive surfaces have been compared in terms of design workflow. The analyses showed that besides the need for more insight on the performative effects of geometrical rules, there is also a need for a complete computation design system that could host different digital tools: Geometry generation, Performative analyses and Robotic simulation. These tools could be improved by a more careful attention towards a more user-friendly approach based on a proper user-interface and rapid visual performative feedback.

The design of special patterns of reflection and potentially other unconventional acoustic surface such as metamaterials behaviors can be investigated in similar ways. The design process of diffusive surfaces shows, that raising awareness among architect and designers related to the correlation of the performative output and geometrical rules, could lead to a more conscious and efficient design of the entire space.

REFERENCES

1. Haan C., Fricke F.R. An evaluation of the importance of surface diffusivity in concert halls. Appl. Acous. 1997; 51(1): 53-69.
2. Beranek L.L. Concert and opera halls: how they sound. Acoustical Society of America, Woodbury, New York, 1996.
3. Choi Y.J. Effects of periodic type diffusers on classroom acoustics, Appl. Acoust. 2013; 74: 694-707.
4. Onaga H., Rindel J.H., Acoustic characteristics of urban streets in relation to scattering caused by building façades, Appl. Acoust. 2007; 68 (3): 310-325.
5. Badino E., Manca R., Shtrepi L., Calleri C., Astolfi A., Effect of façade shape and acoustic cladding on reduction of leisure noise levels in a street canyon, Building and Environment 2019;157:242-256.
6. Cox T. J., D'antonio P. Acoustic Absorbers and Diffusers: Theory, Design and Application. Taylor and Francis, New York, USA, 2017.
7. Peters B., Olesen T. Integrating Sound Scattering Measurements in the Design of Complex Architectural Surfaces. 28th eCAADe Conference Proceedings, 2010, 481 – 491.
8. Reinhardt D., Cabrera D., Jung A., Watt R., Towards a Micro design of Acoustic surfaces: Robotic fabrication of complex pattern geometries. In Reinhardt et al. Robotic Fabrication in Architecture, Art and Design, 2016: 137-149.
9. Jensen, M.B. Robotic Fabrication of Acoustic Geometries - an explorative and creative design process within an educational context. Archi DOCT 2019; 6 (2): 34-45.
10. Shtrepi L., Menichelli J., Astolfi A., Mendez T., Masoero M. Improving scattering surface design with rapid feedback by integrating parametric models and acoustic simulation, J Acoust Soc Am. 2017; 142.
11. Oxman R. Thinking difference: Theories and models of parametric design thinking, Des. Stud. 2017; 52: 4-39.
12. Wortmann T. and Tuncer B. Differentiating parametric design: Digital workflows in contemporary architecture and construction, Design Studies 2017; 52: 173-197.
13. Cox T. J., Dalenback B.-I. L., D'Antonio P., Embrechts J. J., Jeon J. Y., Mommertz E., Vorländer M., A Tutorial on Scattering and Diffusion Coefficients for Room Acoustic Surfaces, Acta Acust united Ac. 2006; 92: 1-15.
14. ISO 17497: Acoustics -- Sound-scattering properties of surfaces -- Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room, 2004.
15. ISO 17497-2:2012: Acoustics -- Sound-scattering properties of surfaces -- Part 2: Measurement of the directional diffusion coefficient in a free field, 2012.
16. Vorländer M., International Round Robin on room acoustical computer simulations. Poc. ICA 95; 26-30 June 1995, Trondheim, Norway, 1995.
17. Shtrepi, L.; Astolfi, A.; Puglisi, G.E.; Masoero, M.C. Effects of the Distance from a Diffusive Surface on the Objective and Perceptual Evaluation of the Sound Field in a Small Simulated Variable-Acoustics Hall. Appl. Sci. 2017; 7: 224.
18. Shtrepi, L. Investigation on the diffusive surface modeling detail in geometrical acoustics based simulations. J Acoust Soc Am. 2019; 145: EL215-221.

19. Embrechts J.-J., De Geetere L., Vermeir G., Vorländer M., Sakuma T. Calculation of the Random-Incidence Scattering Coefficients of a Sine-Shaped Surface. Acta Acust united Ac. 2006; 92(4): 593-603.
20. Embrechts J.-J., Billon A.Theoretical Determination of the Random- Incidence Scattering Coefficients of Infinite Rigid Surfaces with a Periodic Rectangular Roughness Profile. Acta Acustica united with Acustica 2011, 97(4): 607-617.
21. Schmich-Yamane I., Malgrange M., Rougier C. How absorptive can a diffuser be to accurately measure random incidence scattering coefficients? Proc ICA 2013; 2-7 June 2013; Montreal, Canada. 2013.
22. Hargreaves T. J., Cox T. J., Lam Y. W., D'Antonio P. Surface diffusion coefficients for room acoustics: Free-field measures. J Acoust Soc Am. 2000; 108(4): 1710-1720.
23. Cox T. J. The optimization of profiled diffusers. J Acoust Soc Am. 1995; 97(5): 2928-2936.
24. Redondo J., Sanchez-Perez J. V., Blasco X., Herrero J. M., and Vorländer M. Optimized sound diffusers based on sonic crystals using a multiobjective evolutionary algorithm. J. Acoust. Soc. Am. 2016; 139 (5): 2807–2814.
25. Herrero J. M., Blasco X., Sanchez-Perez J. V., J. Redondo J. Design of sound phase diffusers by means of multiobjective optimization approach using ev-MOGA evolutionary algorithm. Struct Multidisc Optim 2016; 53: 861–879.
26. Orlowski R. J. Shape and diffusion in the design of music spaces. Proc ICA 2001; Rome, Italy, 2001.
27. Cox T. J. Designing curved diffusers for performance spaces, Audio Eng. Soc. 1996; 44: 354–364.
28. Takahashi D. Development of optimum acoustic diffusers. JASJ (E) 1995; 16(2): 51-58.
29. Bonwetsch T., Baertschi R., Oesterle S. Adding Performance Criteria to Digital Fabrication Room-Acoustical Information of Diffuse Respondent Panels, Proc. 28th ACADIA, in Silicon + Skin, Biological Processes and Computation, Minneapolis, Minnesota 2008. 364-369.
30. Whitehead, H. Laws of form. In B. Kolarevic (Ed.), Architecture in the digital Age: Design and manufacturing, Taylor & Francis, 2003, p. 89-113.
31. Jiménez N., Cox T. J., Romero-García V., Groby J.-P. Metadiffusers: Deep-subwavelength sound diffusers. Scientific reports, Nature, 2017; 7: 5389.
32. Zhu Y., Fan X., Liang B., Cheng, J., Jing Y. Ultrathin Acoustic Metasurface-Based Schroeder Diffuser, Physical Review 2017; 7, 021034.
33. Bradley D. T., Sharma A., Adelgren J. Assessing the effectiveness of geometrically modified pyramidal diffusers. Proc ASA; 2-6 December 2013; San Francisco, USA, 2013.
34. Lin F.-M., Hong P.-Y., Lee C.-Y. An experimental investigation into the sound-scattering performance of wooden diffusers with different structures. Appl. Acoust. 2010; 71(1): 68-78.
35. Kim Y. H., Jang H. S., Jeon J. Y. Characterizing diffusive surfaces using scattering and diffusion coefficients. Appl. Acoust. 2011; 72(11): 899-905.
36. Tsuchiya Y., Lee H., Sakuma T. Scale model measurements of the scattering coeffcients of rib/block structure walls, AIJ J. Technol. Des. 2013; 19(41): 175-178.
37. Lee H., Tsuchiya Y., Sakuma T. Acoustic scattering characteristics of Penrose-tiling-type diffusers, Appl. Acoust. 2018; 130:168–176.
38. Jeon J. Y., Lee S. C., Vorländer M. Development of scattering surfaces for concert halls. Appl. Acoust. 2004; 65(4): 341-355.
39. Shtrepi L., Astolfi A., D'Antonio G., Vannelli G., Barbato G., Mauro S., Prato A., Accuracy of the random-incidence scattering coefficient measurement, Appl. Acoust. 2016; 106: 23–35.
40. Sakuma T., Lee H., Recent topics in acoustic scattering coefficient determination for wall surfaces. Proc ISRA 2013; 9-11 June2013; Toronto, Canada, 2013.
41. De Geetere L., Vermeir G. Investigations on real-scale experiments for the measurement of the ISO scattering coefficient in the reverberation room. Proc Forum Acusticum 2002; 16 - 20 September 2002; Sevilla, Spain, 2002.
42. Bibby C., Hodgson M., Characterization and improvement of absorption and scattering by profiled architectural surfaces without specialized test facilities. Appl. Acoust. 2011; 72(11): 889-898.
43. Cox T. Room acoustic diffusers: pyramids and wedges. Proc ICSV 24, 22-27 July, 2017, London; 2017.
44. Janssen, P., Chen, K. W. Visual dataflow modelling: A comparison of three systems. Proc CAAD Futures; 4-8 July 2011; Liege, Belgium 2011. p. 801-816.
45. Pahyderm website: http://www.perspectivesketch.com/pachyderm/index.php (last viewed 31 May 2019)
46. Oxman R. Informed tectonics in material-based Design, Design Studies 2012; 33 (5): 427-445.
47. Kohler, M Gramazio, and J Willmann. The robotic touch: How robots change architecture, Park Books Zurig, Switzerland, 2014.
48. Gursoy B., Ozkar M., Visualizing making: Shapes, materials, and Actions, Des. Stud. 2015; 41: 29-50.