INTEGRATED PHOTOVOLTAIC NOISE BARRIERS FOR INFRASTRUCTURE APPLICATIONS

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Abstract

Mitigating environmental noise from transport infrastructure remains a major challenge in densely populated areas. At the same time, the transition towards low-carbon energy systems requires large-scale deployment of solar photovoltaics (PV). In this context, Photovoltaic Noise Barriers (PVNBs) offer a multifunctional solution combining noise mitigation and renewable electricity generation within existing infrastructure corridors. This paper presents the development and assessment of innovative PVNB concepts within the European projects SEAMLESS and INCREASE. Both projects investigate the integration of photovoltaic modules into acoustic barriers through different design approaches. SEAMLESS focuses on optimizing conventional PV noise barriers, balancing acoustic performance, structural behavior, and energy yield. In contrast, INCREASE explores micro-perforated panel (MPP) solutions to enhance broadband sound absorption and reduce reflections associated with rigid PV surfaces. A multidisciplinary design methodology was adopted, combining acoustic, mechanical, and photovoltaic requirements. FEM simulations were used to optimize the proposed designs and assess the acoustic performance of the developed concepts. In addition, a full-scale SEAMLESS prototype was experimentally validated through in situ reflection and transmission measurements in a free-field environment using the Adrienne method. The results confirm the feasibility and potential of PVNBs as sustainable solutions for transportation noise mitigation while simultaneously contributing to renewable energy generation.

Keywords: *photovoltaic noise barriers, transport infrastructure noise, micro-perforated panels, acoustic performance, sustainable infrastructure*

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1. Introduction

Transportation noise from road and railway infrastructures and the need for increased renewable energy generation have driven the development of multifunctional solutions such as Photovoltaic Noise Barriers (PVNBs) [1]. By integrating photovoltaic modules into conventional noise barriers, PVNBs provide both noise mitigation and renewable electricity generation without additional land use. However, the incorporation of photovoltaic panels introduces acoustic challenges due to their reflective nature, requiring integrated design strategies that optimize both acoustic and energy performance. In this context, MPPs and resonator-based systems have emerged as promising alternatives to conventional fibrous absorbers, offering enhanced durability, weather resistance, recyclability, and reduced maintenance. Recent advances in MPP technologies further improve the compatibility between acoustic treatment and photovoltaic integration, enabling more efficient multifunctional barrier solutions [2].

Recent European research initiatives have accelerated the development of innovative PVNB concepts. In this context, the SEAMLESS and INCREASE projects address complementary approaches for next-generation PVNB systems. SEAMLESS focuses on optimizing and validating conventional PVNB configurations to achieve an optimal balance between acoustic performance, structural requirements, and photovoltaic efficiency, while INCREASE investigates advanced acoustic solutions based on microperforated panels and resonator systems integrated into the barrier structure to enhance sound absorption and reduce reflections from photovoltaic surfaces.

This work presents and evaluates novel PVNB concepts developed within both projects through a multidisciplinary design methodology integrating acoustic, mechanical, and photovoltaic requirements. Ray-tracing simulations were applied to optimize system positioning and sound propagation performance, whereas FEM simulations were used to

optimize the acoustic behaviour of microperforated absorbing systems.
Experimental validation combined laboratory and full-scale testing. Laboratory investigations focused on optimizing microperforated panel and resonator configurations, while full-scale assessments evaluated the SEAMLESS prototype performance and its compliance with CE marking requirements, supporting its commercialization potential. The results provide valuable insights into the feasibility and effectiveness of integrated PVNBs as sustainable infrastructure solutions capable of simultaneously mitigating transportation noise and generating renewable energy.
Beyond technical performance, both projects address industrialization, aesthetics, built-environment integration, and social acceptance through the involvement of the entire value chain, including material manufacturers (ONYX Solar), engineering companies (BECSA), environmental, photovoltaic, and acoustic research organizations (TECNALIA), and end users responsible for the management of linear transport infrastructures. These include INTERBIAK, the infrastructure agency of the Provincial Council of Bizkaia responsible for the road network, and Euskal Trenbide Sarea (ETS), the public manager of the Basque railway network. These entities also provide the infrastructure required for the deployment of demonstration sites and real-scale validation activities.
The present paper focuses specifically on the results obtained from the research activities aimed at improving the acoustic effectiveness of the prototypes developed within both projects.

2. PVNB Concepts and Design Methodology

A common feature of both projects is their market-oriented conception from the outset. To ensure commercial viability, the designs were developed in accordance with the minimum requirements for noise barriers in transport infrastructures and the electrotechnical standards applicable to outdoor electrical installations. The acoustic design of the SEAMLESS solution is constrained by the photovoltaic technology employed. In the SEAMLESS project, bifacial photovoltaic modules are used, enabling electricity generation from both sides of the panel. This feature limits the possibilities for modifying the acoustic reflection properties of the photovoltaic surface itself, thereby requiring the sound-absorbing treatment to be located outside the photovoltaic system.
Following the evaluation of several configurations for the placement of acoustic absorbing materials, a design incorporating a 1 m high lower section composed of highly absorptive metallic acoustic panels was selected. The combination of this absorbing section with different photovoltaic panel inclinations allows the barrier to be installed at the roadside while preventing undesirable acoustic effects on the side that is not protected by the barrier.
In contrast, the INCREASE concept is based on the use of monofacial photovoltaic modules, which allow sound-absorbing treatments to be integrated into the rear side of the system. Under this approach, the design focuses on the development of integrated solutions capable of simultaneously providing photovoltaic energy generation and acoustic attenuation, while defining a modular system that can be configured to meet the specific requirements of different noise barrier applications and environmental conditions.
For the development of the absorbing component of the module, novel acoustic solutions are being investigated that avoid the use of conventional fibrous materials. Instead, the proposed designs rely on multilayer microperforated acoustic technologies, which provide sound absorption through their engineered geometric configuration and acoustic impedance characteristics. This approach offers a more sustainable, durable, and maintenance-friendly alternative for outdoor applications while maintaining high acoustic performance.

2.1 Additional Mechanical Requirements.

In addition to conventional acoustic requirements, photovoltaic noise barriers (PVNBs) must also comply with structural, mechanical, and safety criteria associated with the integration of photovoltaic modules. Since specific PVNB standards are not yet available, current designs are based on the combined application of existing regulations for both noise barriers and photovoltaic systems .
A major design challenge for photovoltaic noise barriers (PVNBs) is ensuring resistance to environmental loads, including wind, snow, and accidental impacts. The integration of photovoltaic modules alters load distribution and increases structural demands, requiring robust supporting structures, foundations, and connections to guarantee long-term safety and durability. Structural integrity has been identified as a critical factor for the large-scale deployment of PVNBs in road and railway infrastructures exposed to severe climatic conditions [3]. The installation height of photovoltaic modules also requires careful consideration. Positioning the modules above ground level helps reduce the risk of vandalism, facilitates maintenance operations, and minimizes shading effects caused by surrounding vegetation. Furthermore, the durability of materials and the accessibility of both electrical and structural components are essential factors influencing the long-term reliability of the system. Road safety considerations for PVNBs include the assessment of glare from photovoltaic module surfaces, which depends on factors such as barrier orientation, module inclination, topography, and traffic conditions. Consequently, PVNB design requires a multidisciplinary approach balancing acoustic performance, structural integrity, energy generation, safety, aesthetics, and economic feasibility to ensure successful implementation in transportation infrastructure.
The following sections present the progress achieved through the combined developments of both projects, with particular emphasis on the results obtained from the acoustic assessment.

3. Results and Discussion

3.1 Design Methodology and Evaluation

The development process began with the collaborative identification and conceptualization of viable PVNB solutions involving stakeholders across the value chain, resulting in several product families integrating noise mitigation and photovoltaic energy generation. Numerical simulations were then performed to assess the acoustic performance of different geometrical configurations and component properties, enabling the definition of optimal performance targets. The selected solutions were subsequently validated through experimental testing, as described in the following sections.

3.2 Acoustic Simulations

To this end, acoustic propagation and reflection effects were evaluated using ray-tracing simulations, while the influence of system geometry was investigated through FEM and BEM simulations. Several infrastructure configurations were considered, including different numbers of traffic lanes and barrier installations on either one or both sides of the roadway, as illustrated in the following figures:

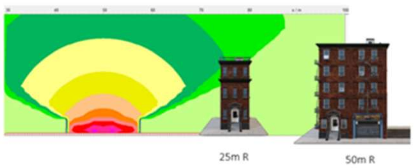


Figure 1. Configurations considered for acoustic propagation simulations.

For each configuration, multiple barrier inclination angles were analysed. This approach was intended not only to assess acoustic performance but also to identify the most favourable configurations for photovoltaic energy generation. A database of simulation results was therefore established as a function of infrastructure location and solar orientation. In parallel, the optimum configuration for achieving maximum sound absorption in bifacial photovoltaic noise barriers was investigated, while minimizing the visual impact of the installation.

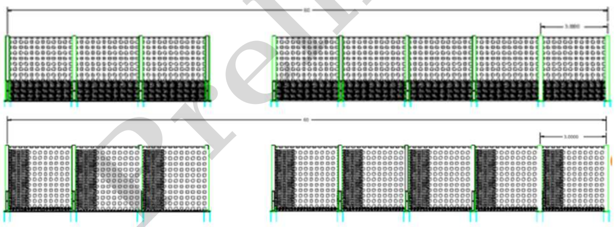


Figure 2. Configurations analysed for acoustic absorption performance.

Based on the results of these simulations, the SEAMLESS photovoltaic noise barrier concept was defined for implementation within the project, while also providing a foundation for the development of future configurations and design variants. To evaluate the influence of the geometrical features of the modules integrating both acoustic and photovoltaic functionalities, additional simulations were performed using finite element and boundary element methods. These analyses enabled the identification of the optimal arrangement of both the photovoltaic modules and the sound-absorbing components within the overall system design.

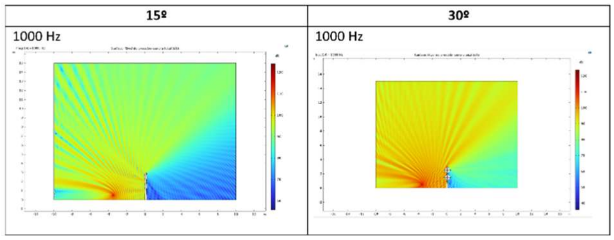


Figure 3. Simulations with different panel orientations and tilt angles.

Different panel orientations and inclination angles were evaluated, considering solar irradiation and acoustic reflection effects. The results indicated that a **30° inclination** provides the best compromise between energy yield and acoustic behaviour for the demonstration site conditions.

As a result of these simulation activities, a modular system combining sound absorption and photovoltaic energy generation has been developed and is currently undergoing the process of industrial protection. In addition, an innovative sound-absorbing system based on multilayer microperforated materials is being developed through numerical simulations using Finite Element Models (COMSOL Multiphysics®). These simulations have investigated different microperforation geometries and configurations, considering both state-of-the-art acoustic design principles and the manufacturing capabilities available within the industrial environment for the production of microperforated materials.

The numerical analyses have enabled the optimization of the multilayer absorber architecture, providing valuable insights into the influence of perforation parameters, layer arrangement, and cavity configurations on the overall acoustic performance. The resulting designs aim to achieve high sound absorption levels while eliminating the need for conventional fibrous materials, thereby improving sustainability, durability, and suitability for outdoor applications.

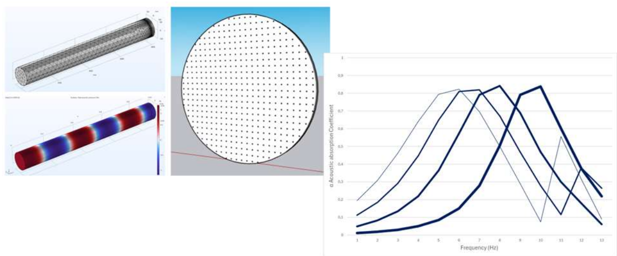


Figure 4. FEM model of the impedance tube and calculated normal-incidence absorption coefficient for four backing cavity depths.

Based on the results obtained from the numerical analyses and considering the materials available within the scope of the project, a modular sound-absorbing system was designed and developed. The resulting solution, which is currently undergoing industrial protection procedures, has been manufactured for subsequent experimental validation. The design of the absorber was guided by both acoustic performance requirements and practical manufacturing considerations, ensuring compatibility with industrial production processes while maintaining the modularity required for integration into photovoltaic noise barriers. Experimental testing of the manufactured prototypes is being carried out to validate the acoustic performance predicted by the numerical simulations and to assess the suitability of the proposed solution for large-scale deployment in transportation infrastructure applications.

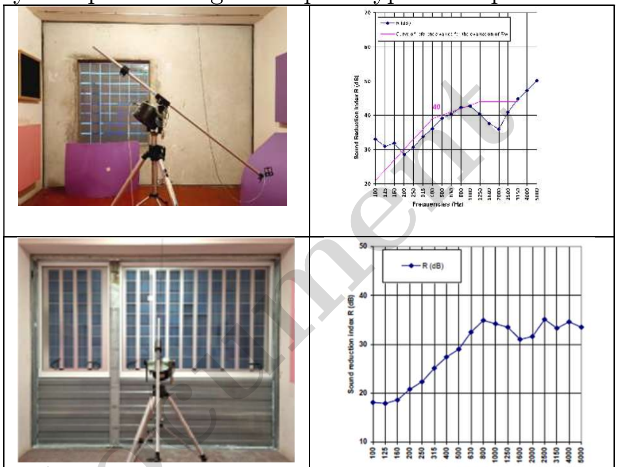
3.3 Experimental validation

Experimental work was initially conducted on small-scale prototypes in laboratory conditions to determine the properties of the constituent materials to be employed, including both the photovoltaic components and the integrated system as a whole. Emphasis was placed on verifying the technical and mechanical feasibility of the proposed solutions at an early stage of development.
To this end, the principal mechanical tests specified in EN 1794-2:2025 for road traffic noise-reducing devices were carried out, in accordance with the requirements established for CE marking under UNE-EN 14388. These tests were intended to evaluate the structural integrity, safety, and suitability of the proposed materials and assemblies for their intended application as photovoltaic noise barriers.
The results confirmed the mechanical viability of the selected solutions and provided the necessary input for the subsequent stages of prototype development and full-scale validation. Examples of the experimental testing procedures and test setups are shown in the following figures.

Risk of detached fragments | Brushwood testing

Figure 5. Mechanical testing on prototypes.

The acoustic performance of the photovoltaic material was also evaluated to ensure a sound insulation index, DLR, greater than 32 dB. Subsequently, comprehensive laboratory acoustic testing was carried out to characterize the behaviour of both the photovoltaic elements and the integrated system under controlled conditions. These investigations were performed to verify the suitability of the selected photovoltaic modules for application in noise barrier systems, ensuring that the incorporation of energy-generation functionality did not compromise the acoustic requirements of the barrier. The laboratory campaign included the assessment of airborne sound insulation and other relevant acoustic parameters, providing experimental data for comparison with the numerical predictions obtained during the simulation phase.
The results confirmed that the photovoltaic components satisfied the minimum acoustic insulation requirements established for the project, thereby validating their integration within the proposed PVNB configurations. Furthermore, the experimental findings provided valuable input for the optimization and final design of the combined photovoltaic and acoustic system prior to large-scale prototype development.



Sound Transmission test

Figure 6. Acoustic tests on prototypes.

Finally, the simulated performance of the multilayer microperforated sound-absorbing system was experimentally verified through impedance tube measurements, conducted in accordance with the relevant standardized test procedures. A wide range of configurations were evaluated, including variations in perforation geometry, perforation ratio, panel thickness, and backing cavity depth.

Figure 7. Prototype MPP.

The primary objective of this experimental campaign was to establish a robust correlation between the numerical predictions and the measured acoustic behaviour of the proposed absorber concepts. The results enabled the validation and refinement of the simulation models, providing a reliable basis for predicting the performance of alternative design configurations.
Furthermore, the experimental findings were used to optimize the acoustic design of the absorber and to define the final product configuration, considering not only sound absorption performance but also practical considerations related to manufacturing, assembly, durability, and large-scale industrial deployment. This combined numerical and experimental approach facilitated the development of a technically viable and

acoustically efficient solution suitable for integration into next-generation photovoltaic noise barriers.

The normal-incidence sound absorption coefficient was measured in a Kundt tube for two MPP configurations, each tested with four backing air-cavity depths. As the cavity depth increases, the absorption peak shifts toward lower frequencies, confirming the strong influence of the rear cavity on the resonant behavior of the absorber. In the figure, thicker curves correspond to smaller air-cavity depths, whereas thinner curves represent larger air-cavity depths.

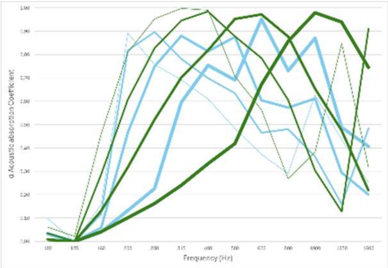


Figure 8. Measurement of the normal-incidence sound absorption coefficient for two microperforated panel (MPP) configurations using the Kundt tube method.

The results demonstrate that MPPs with different air cavity depths achieve sound absorption across the entire target frequency range. The normal-incidence sound absorption coefficient of the coupled MPP system was also measured using a Kundt tube. In this configuration, the two MPPs were arranged in series and separated by a 5 mm air cavity.

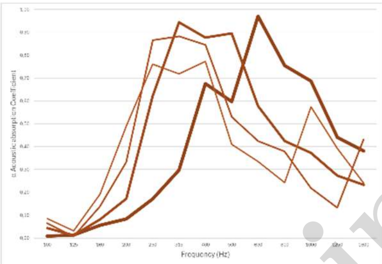


Figure 9. Measurement of the normal-incidence sound absorption coefficient for the coupled microperforated panel (MPP) configurations using the Kundt tube method.

Overall, a good agreement was observed between the numerical predictions and the experimental results obtained for the tested samples, confirming the validity of the adopted modeling approach. The discrepancies between simulations and measurements can be mainly attributed to manufacturing imperfections inherent to the additive manufacturing process. Specifically, the perforations exhibited irregular geometries and dimensional inaccuracies, burrs were present along the perforation edges, and the rear surfaces showed a rough. While Maa's model assumes perfectly circular and smooth perforations, the actual samples deviated from these ideal conditions, leading to modifications in the acoustic wave propagation within the perforations and consequently affecting the measured acoustic response. Therefore, the observed differences are considered to be primarily related to fabrication tolerances rather than limitations of the theoretical model itself [4].

3.3.1 Experimental assembly

For the SEAMLESS project, an experimental campaign was carried out on the developed photovoltaic noise barrier prototype, which is based on conventional flat photovoltaic modules and has been designed for configurations incorporating varying heights and inclination angles. The objective of this campaign was to verify the acoustic performance of the system and to establish a validation methodology for assessing the correct functioning of joints, seals, and structural profiles, which are critical components influencing the overall acoustic effectiveness of the barrier. In parallel, a field verification methodology was implemented based on the UNE-EN ISO 1793-5 and UNE-EN ISO 1793-6 standards, which define direct field measurement procedures for determining the intrinsic acoustic characteristics of noise barriers. These standards enable the evaluation of sound reflection and airborne sound insulation under in-situ conditions, providing a reliable framework for assessing the acoustic performance of the complete system after installation. The prototype has been installed at Becsa's warehouse and workshop facility in Almassora.

3.3.2 Measurement Configurations

To obtain as much information as possible regarding the system response at different locations, four measurement configurations were defined: the photovoltaic panel area (2), the vertical profile area (3), the joint between the photovoltaic panel and the sound-absorbing panel (1), and the center of the test specimen (4), where the two photovoltaic panels and the two sound-absorbing panels meet. The purpose was to determine whether sound insulation and sound absorption showed significant differences depending on the measurement location, which could indicate the presence of acoustic leakage paths through the barrier.

Figure 10. Prototype test. Castellón test site.

The results obtained for the four measurement configurations are presented below and compared in order to assess the influence of the measurement location on the airborne sound insulation performance of the system.

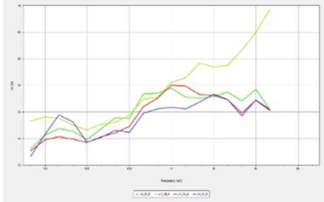


Figure 11. Sound insulation curves

The obtained indices are consistent with the photovoltaic panel design specifications, with DLSI > 27 dB. The photovoltaic panel provides airborne sound insulation values exceeding 30 dB above 1 kHz. Increased sound transmission is observed at the panel joints and profile intersection areas, where DLSI values remain above 23 dB. This is confirmed by the reduction in insulation performance observed at frequencies above 1 kHz, indicating the presence of acoustic transmission paths through these discontinuities. For the final design, special attention will be given to the proper installation and sealing of the insulating gaskets between the panels and the supporting profiles, with the aim of reducing acoustic leakage through joints and interface areas. The acoustic reflection results for the four measurement configurations are presented below and compared in order to evaluate the influence of the measurement location on the sound reflection performance of the system.

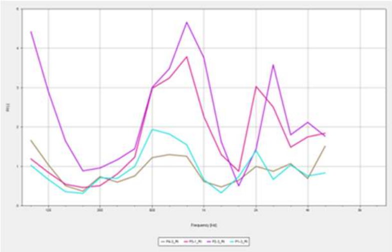


Figure 12. Sound reflection curves

The obtained index is consistent with the photovoltaic panel design specifications, with DLRI values exceeding 15 dB, confirming the reflective acoustic behaviour expected from the glazed photovoltaic surface. In the areas containing sound-absorbing material, the DLRI values remained between 10 dB and 15 dB, demonstrating a reduction in sound reflection compared with the photovoltaic panel areas. As a general conclusion of the acoustic barrier testing campaign, the designed prototype has demonstrated performance levels consistent with the design expectations. The results confirm the suitability of the proposed solution for application as a road traffic noise reducing device. Consequently, the prototype may be considered a viable product for road traffic noise barriers, capable of meeting the environmental, acoustic and structural requirements required for certification and market acceptance under CE Marking in accordance with EN 14388.

4. Conclusions and Next Steps

The results obtained demonstrate the feasibility of advanced tools and methodologies for the simulation, design, and performance assessment of photovoltaic noise barriers, supporting the optimization of acoustic and photovoltaic performance and compliance with technical requirements.

From a product development perspective, a functional pre-commercial prototype corresponding to the SEAMLESS project is currently available. This prototype is scheduled for installation along a real traffic corridor in Bizkaia (Basque Country, Spain), at a site provided by the Provincial Council of Bizkaia and the public infrastructure company INTERBIAK. The demonstrator will have an overall length of 75 m and a height of 4 m, providing a unique opportunity to evaluate the acoustic, photovoltaic, and operational performance of the system under real-world conditions. With regard to the multifunctional module combining electricity generation and sound absorption, the initial design configurations, including both the structural geometry and the acoustically functional materials, have already been defined for full-scale prototyping. This development, which is being carried out within the framework of the INCREASE project, is currently undergoing industrial protection procedures. Consequently, images and detailed descriptions of the final product configuration and product families cannot yet be disclosed. During the current and forthcoming year, the design of the prototype and the final demonstrator product will be completed and prepared for installation at a demonstration site located on a railway infrastructure provided by Euskal Trenbide Sarea (ETS) in Bizkaia (Basque Country, Spain). Subsequent activities will focus on the comprehensive validation of both the acoustic and photovoltaic performance of the developed system under representative operating conditions. These demonstrations will constitute a key step towards the large-scale deployment of multifunctional photovoltaic noise barriers in transportation infrastructure applications.

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References

[1] Q. Wu, X. Zhang, and Q. Wang, "Integrating Renewable Energy in Transportation: Challenges, Solutions, and Future Prospects on Photovoltaic Noise Barriers," Sustainability, vol. 16, no. 6, Art. no. 2358, 2024,

[2] I. Yamagiwa, M. Horio, S. Nakaoka, and T. Yamada, "Eco Kyuon—Microperforated Sound Absorbing Panel," Kobe Steel Engineering Reports, vol. 58, 2008.

[3] H. M. Kim, S. Yun, J. S. Kong, and J. C. Kim, "Structural Safety Analysis of Photovoltaic Noise Barriers Using One-Way Fluid-Structural Interaction Analysis," Journal of Mechanical Science and Technology, vol. 39, no. 6, pp. 3217–3228, 2025.

[4] K. Sakagami, M. Kusaka, T. Okuzono, and S. Nakanishi, "The Effect of Deviation Due to the Manufacturing Accuracy in the Parameters of an MPP on Its Acoustic Properties: Trial Production of MPPs of Different Hole Shapes Using 3D Printing," Acoustics, 2(3),605–616, 2020.