Recent Advances on Perforated Panels for Sound Absorption Applications

Jesús Carbajo, Nicholas Xuanlai Fang and Sang-Hoon Nam

Abstract—**Perforated panel sound absorbers have become one of the most promising passive noise control solutions not only because of their excellent sound absorption performance but also because of their high structural strength and durability. These features make them an interesting eco-friendly alternative to traditional porous fibrous media or foams, especially in those scenarios implying aggressive environmental agents (e. g. strong wind, heavy rain…) or severe working conditions (e. g. turbines, jet engines…). Many engineering applications of these systems can be found in practice ranging from noise barriers and room acoustics conditioning to the design of muffler devices and MRI scanners. This work briefly reviews the fundamentals of classical perforated panel sound absorbers and reports some recent advances in their use for sound absorption applications.**

Index Terms—**Acoustics; sound absorption; perforated panels.**

I. INTRODUCTION

Noise pollution is a problem of major concern because of the harmful effects on human health and the negative impact on the environment. In this context, the scientific community together with industrial partners and public authorities are working together on the development of systems that let reduce noise. Among these, passive sound absorbers have become one of the most-extended solutions, being the perforated panel sound absorbers of great interest due to their improved structural features when compared to conventional porous media. Although generally used as a protective covering for such media, when backed by an air cavity the resulting panel system may work as an acoustic resonator for sound absorption itself. To improve the low-frequency absorption performance and absorption bandwidth of these resonators, many authors have proposed different configurations throughout the years. Maa [1] proposed the use of panels whose perforations are sub-millimetric in size resulting in the so-called Micro-Perforated Panel (MPP) sound absorbers. Subsequently, he analyzed their wideband capabilities by using double-layer MPP arrangements [2]. Some other examples are the study of perforated panels with viscous energy dissipation enhanced by orifice design carried out by Randeberg [3], taking advantage of the vibrational response of thin perforated panels [4], the use of multiple sizes of holes investigated experimentally by Miasa et al. [5], or the parallel arrangement of MPPs [6]. All of these and many other studies served to a great extent as a reference to further developments on this topic, a brief review of the fundamentals of classical perforated panel sound absorbers, and a summary of some recent works being the main aim of this work.

II. CLASSICAL PERFORATED PANEL SOUND ABSORBER

A perforated panel typically consists of a flat rigid surface with periodically arranged perforations such as circular holes or slits, the attenuation of sound being produced by viscothermal losses in these holes (i. e. viscous friction and thermal conduction in the inner air of the perforations). When backed by an air cavity and a rigid wall, a resonant sound absorber is achieved. Let us consider the schematic representation of a classical perforated panel sound absorber as that depicted in Fig. 1. The sound absorption performance of this perforated panel absorber for the case of circular perforations is mainly determined by the radius of the holes, R, the spacing between perforations, b, the panel thickness, d, and the backing air cavity depth, D. Note that the spacing between perforations can be directly related to the perforation rate in the case of periodically distributed perforations by $\phi = \pi R^2/b^2$. In brief, by reducing the radius of the holes the absorption bandwidth can be widened, whereas an increase in the panel thickness or the air cavity depth shifts the peak frequency to lower frequencies.

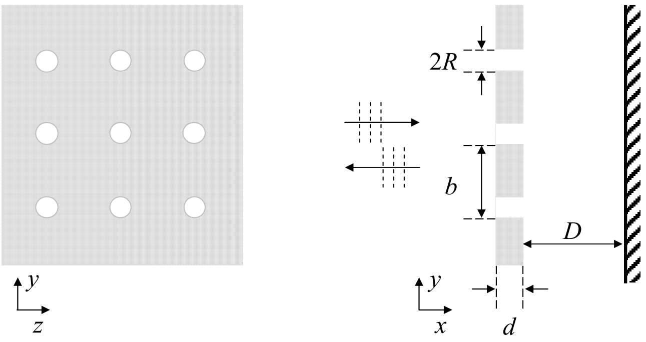

Fig. 1. Schematic representation of a classical perforated panel sound absorber. Left: frontal view. Right: lateral view.

Under plane wave incidence along the x-direction, the acoustic impedance Z of the resonator system is given by

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$$Z = Z_{PP} - jZ_0 \cot\left(k_0 D\right). \quad (1)$$

where Z_{PP} is the transfer impedance of the perforated panel and D is the backing air cavity depth, being Z_0 and k_0 the characteristic impedance and wavenumber in air, respectively.

Once the acoustic impedance of the resonator is obtained, it is straightforward to calculate its sound absorption coefficient as

$$\alpha = 1 - \left|\frac{Z - Z_0}{Z + Z_0}\right|^2 . \quad (2)$$

Much research has been dedicated to determining the transfer impedance of perforated panels throughout the years. Based on early works by Crandall [7] and Rayleigh [8] on sound propagation in narrow tubes, several authors have proposed theoretical models that let predict the acoustic behavior of the whole resonator system [9]. Some relevant contributions are the end correction terms suggested by Ingard [10] to account for the finite thickness of the panels, the formulas for MPPs proposed by Maa [1], or the derivation of an equivalent fluid model as that proposed by Atalla and Sgard [11]. Moreover, some works have analyzed the acoustic properties of perforated panels at high sound pressure levels [12] or orifices under grazing flow conditions [13]. Unfortunately, the above models may present some limitations for the analysis of complex configurations (e. g. a panel with non-uniform perforations). Nevertheless, the high development of computers over the last decades has paved the way for implementations based on numerical methods such as the Finite Element Method (FEM) that allow dealing with those cases. Some recent examples are the use of Computational Fluid Dynamics (CFD) models for the analysis of tapered perforations [14] or the adoption of a full linearized Navier-Stokes formulation for the analysis of a non-homogeneous distribution of the perforations [15].

On the other hand, the acoustic characterization of such absorbers is an essential task both to assess the validity of a predictive model and to analyze extra dissipation phenomena (e. g. the structural resonances). One of the most extended methods to determine their sound absorption coefficient is the transfer function method, whose measurement procedure can be found in the ISO 10534-2 standard [16]. Alternatively, a transfer matrix approach as that described in detail in the ASTM E2611-09 [17] can be used to derive their transfer impedance. Given that the estimation of these acoustic indicators using a prediction model depends on a set of geometrical parameters, it is also common to obtain the values of the latter by using an optimization procedure (e. g. the Nelder-Mead direct search method [18]) that let obtain the best fit between the measured data and the theoretical predictions.

III. INNOVATIVE PERFORATED PANEL SOUND ABSORBERS

Even though classical perforated panel sound absorbers may show an excellent sound absorption performance, apart from interesting aesthetical and structural features, there has been some representative research over the last years that not only show their great capabilities, but also the potential of these devices to be used in diverse scenarios. A representative selection of six of these research works is briefly outlined next.

A. *Parallel-Arranged Extended Tubes (PPET)*

Perforated Panels with Extended Tubes (PPET) have been reported to significantly improve the sound absorption in the low frequencies. The use of extended tubes not only let increase the “effective length” of the panel but also achieves a wider bandwidth when combining parallel-arranged PPETs with different cavities (see Fig. 2a). A theoretical investigation into the performance of the PPET was carried out by Li et al. [19], serving this analysis to obtain an optimal design for practical application in the low-frequency range (120-250 Hz). For this purpose, an optimization procedure based on the simulated annealing algorithm was used to derive a configuration of four parallel-arranged PPETs in a constrained space of 100 mm. Experimental validation of the proposed design was performed by manufacturing a prototype which was tested using an impedance tube setup, results showing a reasonable agreement when compared to predictions.

B. *Coiled Coplanar Air Chamber*

Most perforated panel sound absorbers have a total thickness comparable to the peak absorption wavelength, this being a drawback when designing absorbers for low frequencies. Li and Assouar [20] showed that by coiling up space into the air cavity of the perforated panel absorber an extremely low-frequency acoustic resonator can be achieved. The absorber system consisted of a metasurface composed of a perforated plate combined with a coiled air chamber formed with solid beams as depicted in Fig. 2b. Simulations based on fully coupled acoustic with thermodynamic equations and theoretical impedance analysis were carried out to further understand the underlying physic phenomena. The resulting metasurface possessed a deep subwavelength thickness down to a feature size of $\lambda/223$ achieving perfect sound absorption at 125.8 Hz for a total thickness of the system of 12.2 mm. Furthermore, perfect sound absorption was achieved at the design target frequency. The high efficiency of this type of structure and easy fabrication, when compared to labyrinthine metasurfaces, encourages their use in many applications.

C. *Perforated Honeycomb-Corrugation*

Tang et al. [21] showed that an ultra-lightweight sandwich panel with perforated honeycomb corrugation in its core as shown in Fig. 2c can be an excellent sound absorber. By using small perforations on the top face sheet and the corrugation of a sandwich panel in the inner cavity, an improvement in both the sound absorption within the frequency band 250-2000 Hz and the mechanical performance of the structure (stiffness and strength) was achieved. Additionally, a theoretical model for sound absorption was used to show that wideband sound absorption performance can be also achieved if multiple acoustic resonators are introduced. The resulting multi-functional structure showed to be promising for many engineering applications requiring lightweight constructions with both great acoustic and mechanical properties.

D. Compressed and Micro-Perforated Metal

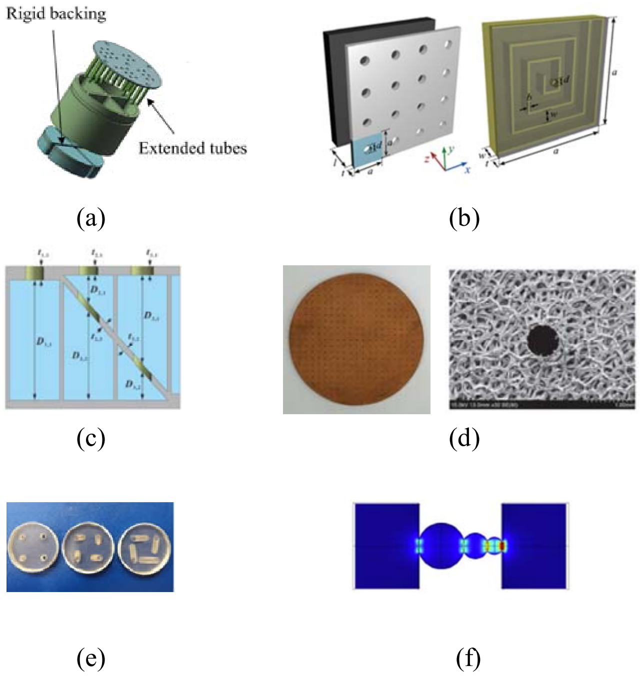
As an alternative to typical perforated panels, Bail et al. [22] proposed a panel fabricated by compression and micro-perforation of a porous metal. The compressed and micro-perforated porous metal panel absorber let achieve better sound absorption than the un-compressed porous metal or a simply micro-perforated spring steel panel. A fourth-order polynomial function was proposed to express the superposition absorption effect resulting from the simultaneous action of the porous and micro-perforated structures. An analysis of the micro-morphology (see Fig. 2d) of the fabricated panel samples provided intuitive explanations of the improvement, which was attributed to the irregular micro-vias from the micro-pores to the micro-perforation.

E. Panel with Oblique Perforations

A perforated panel design that uses perforations aligned obliquely to the panel surface as illustrated in Fig. 2e was proposed in a recent work by the authors [23]. Similar to the PPET, an increase of the “effective length” of the panel allow both improving the low-frequency sound absorption and dealing with limiting space constraints common in many practical scenarios. In doing so, not only a frequency shift of 730 Hz of the resonance frequency of the absorber towards low frequencies can be achieved but also an increase in the peak absorption amplitude provided the geometrical characteristics of the panel are properly chosen. A simple predictive model that relies on the fluid-equivalent theory was developed to investigate the acoustic properties of these absorbers, modified expressions for the geometrical tortuosity and flow resistivity being proposed. Measurements in an impedance tube over additive manufactured samples confirmed previous assertions showing a good agreement when compared to prediction data. Unlike coiled or labyrinthine solutions avoids addressing the air cavity design, which may pose an advantage in terms of further development for practical purposes.

F. Graded spherical perforations

In a recent work by Sailesh et al. [24], the influence of spherical bubble perforations and their grading was investigated by preparing different samples with 3D printed biodegradable material. Both the sound absorption and sound transmission performance of these panel designs were assessed by using the impedance tube method and finite element numerical simulations (see Fig. 2f). Results for different sizes of the spherical bubbles and different types of patterns of graded perforations revealed an enhanced sound absorption performance in the low-frequency range up to 1000 Hz. The authors suggest that these solutions can be effectively used in soundproofing applications in the building and transportation sectors.



(a) (b)

(c) (d)

(e) (f)

Fig. 2. Innovative perforated panel sound absorbers: (a) parallel-arranged extended tubes (PPET) [19]; (b) coiled coplanar air chamber [20]; (c) perforated honeycomb-corrugation [21]; (d) compressed and micro-perforated metal [22]; (e) panel with oblique perforations [23]; and (f) graded spherical perforations [24].

IV. CONCLUSION

In summary, perforated panel sound absorbers show higher durability and structural strength capabilities than conventional porous media. These advantages make these resonator systems provide a wide range of possibilities in many research fields and disciplines of engineering. On the other hand, the incessant development of additive manufacturing techniques poses a new scenario for the conception of innovative designs like those reviewed in this work. In this regard, it may turn out of great interest to also develop new characterization procedures and perhaps to define additional absorption performance indicators. All the same, there is still a need for cost-effective fabrication processes that ease these fabrication procedures to be more extensively adopted in practice. Extending these techniques into the acoustic materials industry will presumably be a challenge to be faced in the forthcoming years.

ACKNOWLEDGMENT

J. C. would like to thank the Organizing Committee of IcETRAN 2022 for the invitation to the Section of Acoustics and also express gratitude to dr. Dejan G. Ćirić for the proposal.

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