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ACOUSTIC 3D SPACER FABRICS IN THE FRAME OF ACOUSTIC MATERIALS. LIMITATIONS AND POTENTIALITIES.

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ABSTRACT

Three-dimensional (3D) spacers prove characteristics in structures and performance which can be to be the main object of a high number of research and applications in specialist markets (from small medical devices to large engineering structure) where the demands of high performance are severe. Nevertheless, much of the research has come from academia and there are few relatively small companies that, even if have expertise, lack the resources to develop R&D programmes. Among these markets, applications in acoustic performance demonstrate that 3D spacers fulfil the increasing request of acoustic performance and aesthetic for interior designs [1]. This performance is topic of several papers, but a comprehensive and updated review is missing. The paper presents a systematic review of research that explore the acoustic performance of 3D spacer fabrics. A scientific approach to develop textile based acoustic materials/structures is deeply desired. Desirable features of acoustic materials in terms of ecology and economy must be explored, such as recyclability, light weight, and cost effectiveness. Design is a challenging task because varying material types together with acoustic textiles can be used simultaneously in different shapes, thicknesses, sequences, perforation, and groove properties. It aims to understand the limitations and the potentialities respect to current market of acoustic materials. The paper underlines how the results obtained by the measurement surveys open to new opportunities for room acoustics applications.

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1. INTRODUCTION

Three dimensional spacers (from now on 3D spacers) are a subcategory of three-dimensional (3D) textiles.
3D textiles are developed to overcome the limitations of conventional 2D textiles to be formed from cutting into pieces according to the 3D pattern, and then assembled into a 3D structure. The processes to manufacture 3D textiles respond to the need to fabricate a 3D integrated structure in a single knitting process rather than with extra joining processes. This does not only improve the 3D structural homogeneity (without cutting of continuous filament yarns), but also reduces the waste of expensive materials and manufacturing costs due to the elimination of cutting and making-up operations.

Figure 1. Example of 3D spacer fabric.

Among the four methodologies to produce 3D textiles (woven, braided, non-woven), 3D spacers are knitted and compounded by two horizontal layers and a vertical one, named pile (Fig. 1). The interest in the application of 3d spacer fabrics was facilitated by the possibility to design the two horizontal layers in terms of density and patterns and the internal vertical pile. A deep analysis on the main performance demonstrates that an interest in the acoustic performance of 3d spacer is increasing. The survey is performed with the research platform tool *Scopus* and *Web of science.*

Specifically, the selection of the main keywords to apply in the strings for the semantic research is based on the study on the definition of three-dimensional textiles. They highlight the use of both "three-dimensional textile" and the abbreviation "3D textile" and the keyword "3D fabric" as complementary in the same context and to refer to the same material system.

The five main performance categories are mechanical, acoustic, thermal (and combustion), hydro/thermal and optical properties. For each performance category, the research considers specific subcategories.

The performances of the acoustic category are either acoustic or sound insulation, acoustic wave propagation, sound/acoustic absorption.

As example of the string, it is reported the query for research on bending modulus:

(TITLE-ABS-KEY ("3d textile") OR TITLE-ABS-KEY ("three-dimensional textile*") OR TITLE-ABS-KEY ("3D fabric*") AND TITLE-ABS-KEY ("sound absorption")).*

The analysis of the number of publications per year per category is plotted in Fig. 2. The trend curve (second order polynomial) highlights the increasing interest in the several performances besides the optical properties. In fact, all the trend curves have a squared correlation *r* positive, besides for the optical curve. The semantic survey highlights the increasing interest in exploring and enhancing mechanical, acoustical and thermal performances.

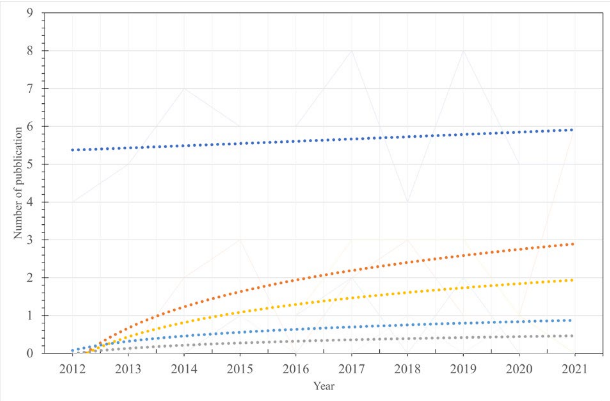

Figure 2. Number of publications per year. The dots lines represent the trend in number of publications per year for each of the categories: mechanical properties in blue, hydro/thermal properties in yellow, acoustic in orange, and thermal and combustion properties in grey, optical properties in red.

Research in acoustical properties, the second in terms of number of research, explores the capabilities to provide high environmental comfort [2] .

The performance categories are also explored in terms of 3d textile typologies. The results are plotted in the Sankey graph depicted in Figure 2. This graphic chart highlights the explored performance according with the 3d textile sub-category. Three-dimensional woven textiles are topic of the higher number of research. Specifically, the top three high numbers of research concern fracture toughness, tensile strength, and Poisson's ratio. The second textiles typology per number of research is the 3d knitted textiles. The performance explored per number of publications are sound absorption, air permeability, and compressive strengths. The compressive strength performances of 3d knitted textiles can be applied for composite reinforcement [3] such as cement-based composites [4]. The high air permeable characteristics of 3d knitted are explored with different bio ceramic additive, to protect against mechanical risk [5] and for wound dressing [6]. The interest in sound absorption is led by the material and physical characteristics that the 3d knitted can have.

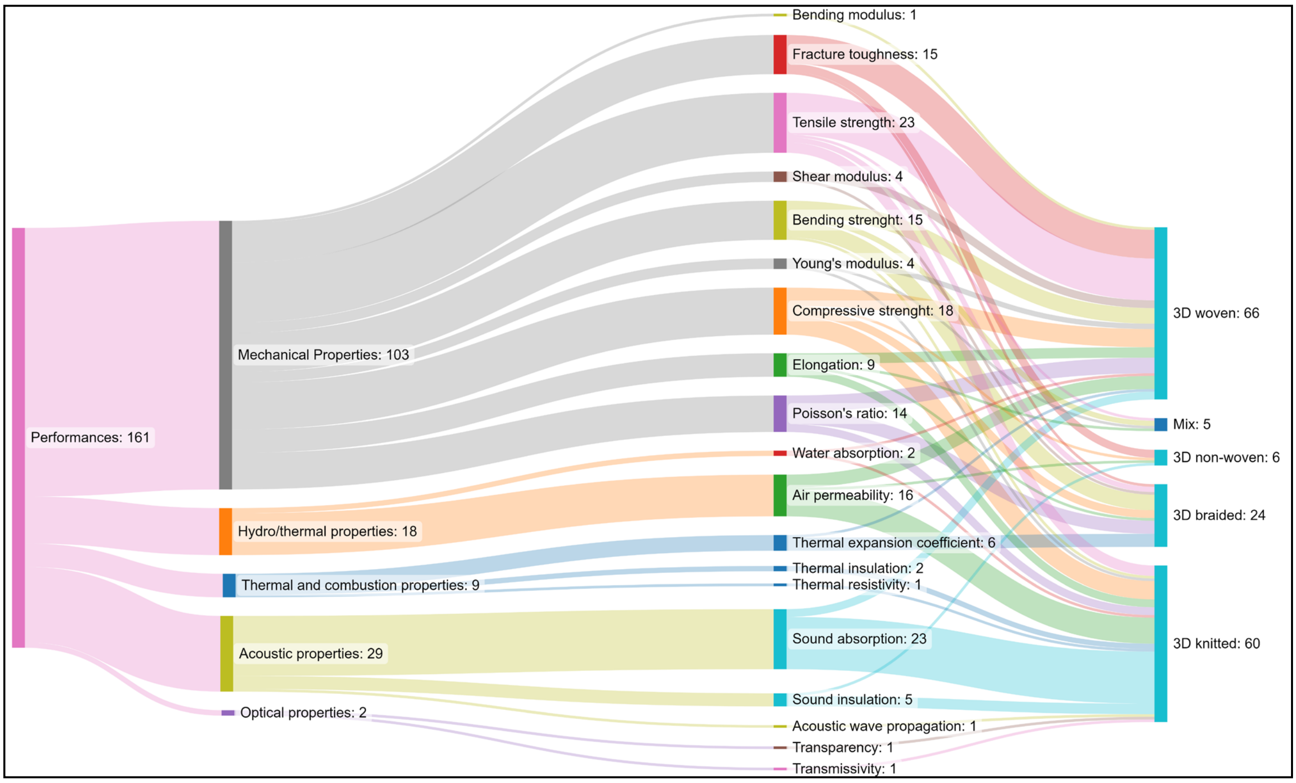

Figure 2. Sankey graphic of the survey on performances of three-dimensional textiles. The graph plots the typology of 3d textile by performance category.

Based on the increasing interest in these material systems for acoustics purposes the paper intends to understand the research background and the results in order to propose a protocol to apply in indoor acoustic comfort (Fig. 3).

2. COMPARISON METHODOLOGY

The indoor sound conditions depend on the number and typology of sound sources, the geometric architecture of the space and the materials that cover the surfaces. Furthermore, room acoustic parameters depend on the location of both the sound source(s) and the receiver in a room. For each combination of space typology (narrow corridor vs open plan space), source type, behaviour and location, the effect of sound absorbing materials on the auditory environment can be determined. The airborne and structure propagation of the sound wave has to be bumped in order to reduce the amount of sonic energy.

This is the principles, for example, of the reverberation time formula theorised by Sabine and Eyring.

Among the acoustic parameters that the absorption coefficient has a key role in the definition of the room acoustic conditions of a space.

The comparison deals with the understanding of 3d spacer fabrics in the frame of acoustic textiles. Therefore, the main sound absorption behaviours are identified and use as main target to compare with. moreover, The characteristics of several typology of 3d spacer fabric such as thickness, material, density, pattern can affect acoustic performance such as absorption coefficient. The analysed research is gathered in the research to see the correlation between performance and 3d spacer.

Most of the case concerns acoustic performance measured in impedance tubes to measure the normal incidence measured in impedance tube.

3. COMPARISON

3.1 Main absorption behavior

There are two broad classes of absorbers: porous absorbents and resonant devices. Figure 4 shows the performance of some absorbers, including both porous and resonant devices. The most common type of porous absorbent is mineral wool, such as fibreglass, and the graph shows the absorption coefficient versus frequency for mineral wool that is 20 mm deep mounted on a rigid backing. Porous absorption is ineffective if it is too shallow compared to wavelength, and consequently, the graph looks like a high pass filter response, with high absorption being achieved from 500 Hz and above and little absorption at bass frequencies. The most efficient way of gaining more low-frequency absorption is to exploit resonance. One way of doing this is to place a perforated sheet in front of the porous absorbent to form a Helmholtz absorber (Fig.
Another approach is to use a thin sheet in front of fibreglass that vibrates and forms a membrane or panel absorber. As these are resonant absorbers, they will have a peak of absorption and a certain bandwidth over which they operate. Two examples are Helmholtz absorber and the membrane design that work at a lower frequency and narrower bandwidth. Getting broadband absorption in one device involves simultaneously exploiting both resonance and porous absorption. This can be achieved by multilayer. This is a device that has layers of different types of fibreglass along with an aluminium foil membrane. Another example is the microperforated wood sample that exploits the resonance of a Helmholtz absorber formed with many tiny holes to aid absorption, along with a backing layer of mineral wool to further increase absorption.

3.2 Acoustic woven, knitted, and non-woven textile comparison

Among the acoustic materials, requested by an AEC market that put always more attention to the environmental indoor quality (IEQ), the acoustic textiles found a prevailing role. Conventional acoustic material still presents limitations in providing a good balance between high sound acoustic performance and environment sustainability. Instead, acoustic textiles minimise the environment impact along with whole life circle and maximise the functional properties. The research on acoustic textile leads to explore the relation between material and structure even if topics such as ecological, economic impact, recyclability, light wight and cost effectiveness remain still interesting. The finding of the relation is challenging due to the several input that define the final shape of the textile. Shapes, thickness, sequences, perforation, and groove properties are only few among those. All of them create a multiple layers-based structure that make hard to have a reliable model to simulate the behaviour.

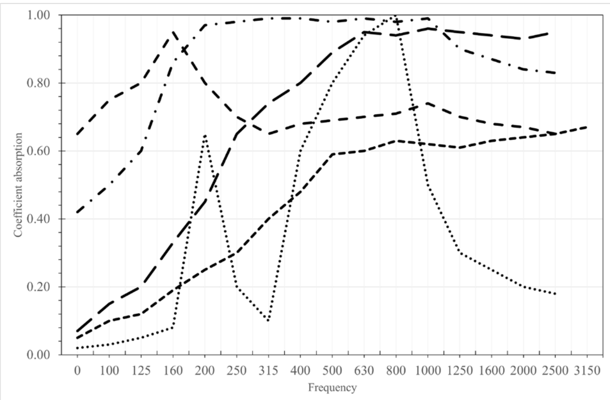

Figure 3. Absorption behavior of common acoustic materials: Polyester fiber (square dash), Resonator (dash), membrane (dash dot), Metamaterial (round dot), mineral wool (long dash).

For these reasons, the advancements in acoustic textiles are slow to be absorbed in current practice. Most of them are compound of natural or recycled fibers cover by non-woven textile (such as felt). The only variation from one producer to the other is the external aesthetic. In terms of acoustic performance, standardized textiles behave by using their characteristics to absorb specific broadband frequencies. In this way, most of their curve of absorbing coefficients is flatten to the middle values (0.5-0.65) (Figure 5). In order to increase the effect on sound conditions, acousticians and engineers have to work with spatial parameter that make the work time-consuming and, in this way, causing an increasing of fees (Fig. 4).

3.2.1 Acoustic woven fabrics

Soltani et al. studied the sound absorption properties of woven fabrics by comparing normal incident sound absorption determined via the impedance tube method [7]. The research explore the relation between sound absorption coefficient and weave typologies: among them here is reported the plain, twill, rips and satin typologies. The fabric structural parameters are shown in

Table 1. As can be seen in Figure 5, the maximum sound absorption coefficient for all samples occurs at a frequency of 1000 Hz. The results show that, the sound absorption coefficient varies in the range of 0.107 to 0.530. The minimum value of the sound absorption coefficient for all samples with the exception of satin weave occurred at a frequency of 250 Hz. The minimum value of the sound absorption coefficient of satin fabric which has the minimum value of noise absorption coefficient or NAC value was found to occur at a frequency of 2000 Hz. This is due to the greater thickness of this fabric in comparison to other weaves. It must be noted that, at a frequency of 2000 Hz, which is an ear-splitting sound, manipulation of sound absorption by textiles irrespective of their structures is rather an arduous task (Fig. 5).

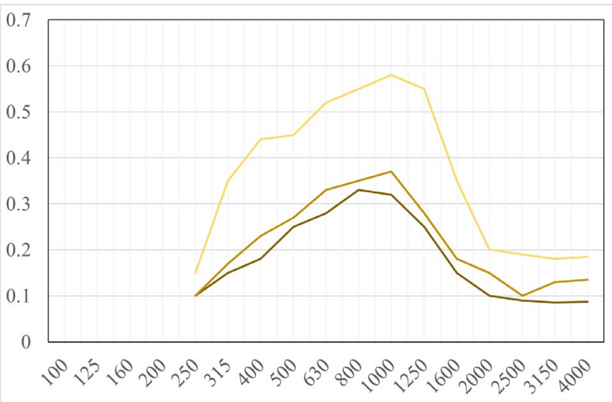

Figure 5. Effect of weave typo on absorption coefficients of plain (RGB 255,217,102), rips (RGB 191,144,0) and satin (RGB 127,96,0).

3.2.2 Acoustic knitted fabrics

Mohammad-Reza, Mehdi, Abosaeed, and Esmail [8] studied the influence of fibres cross-section shape, stitch density, and mechanical modification of surface on sound absorption of weft knitted fabrics. Fabrics with different stitch densities were knitted by yarns consisting of several fibre cross-section shapes. The cross-sectional shape of the fibres has a direct effect on the sound-absorption coefficient, and the plus cross-section had the highest sound-absorption coefficient compared to the circular and oval cross-section. The results are shown in Figure 6.

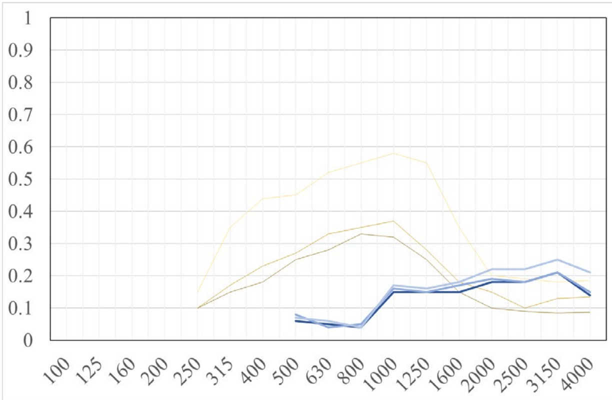

Figure 6. Influence of cross-section shape on sound absorption coefficient for samples C (circular cross-section in blue RGB 180,199,231), D (elliptical cross-section, blue RGB 143,170,220) and E (plus-shaped cross-section in blue RGB 47,85,151). [8]

The elliptical cross-section showed more absorption at high frequencies in comparison to the circular cross-section. The mean sound absorption coefficient of sample D (elliptical cross-section) and sample E (plus-shaped cross-section) has been increased compared to sample C (circular cross-section) by 22.53 and 47.88%, respectively. (Fig. 6)

3.2.3 Acoustic non-woven fabrics

Özdil, Kayseri, and Mengüç [9] investigated the sound-absorption behaviour of non-woven fabrics developed from recycled fibres.
The test results obtained from the impedance tube method are given in Figure 7. According to the results, at low frequencies between 100 and 400 Hz, it can be clearly seen that r-PP, rm-PES, and r-PET surfaces have higher sound absorption coefficient values than the conventional PES and PP fabrics. This is an important point that recycled textile surfaces can be suggestible as sound insulation materials in low frequency band gap (100–400 Hz) as an alternative to the conventional fibers. In addition to this, r-PP material has the highest sound absorption coefficient (over 0.50) among the other recycled products since its lower density and porous structure create a higher friction surface. As the performance at the mid frequencies (400–1600 Hz) is analysed, only PP, r-PP, and rm-PES fabrics have sound absorption coefficient over 0.50. Therefore, these surfaces can be suggested for sound insulation materials to be used at mid frequencies (Fig. 7).

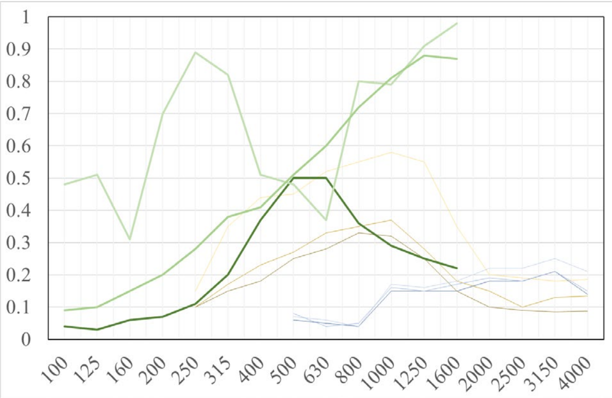

Figure 7. Sound absorption coefficients based on the impedance tube method of r-PP 3D spacer, rm-PES and r-PET.

3.3 Acoustic 3d spacers

The first studies on sound absorption properties of 3D textile were provided to reduce automotive noise [10]. The studies compare six typologies of samples weft-knitted spacer fabrics with different thickness (from 9.35 to 9.45mm) and density (from 86.03 Kg m^{-3} to 216.05 Kg m^{-3}) by providing instrumental tests and theoretical modelling. They found that absorption increases with the decrease in porosity and increased density. However, the effect of density is more predominant in terms of sound absorbency than thickness. The sound absorption of the samples is effective only from 2000 Hz onwards with a narrower absorption frequency range. But the acoustic behaviour of 3d spacer is affected by fabric surface structure, thickness, spacer yarn type fabric surface structure and thickness, their connecting ways, fabric combinations and their arrangement methods according to Liu and Hu [2]. The paper underlines that since the comparable behaviour with microperforated panel, airgap can help in increasing performances at low-middle frequencies. The study compares the behaviour of waft and warp knitted spacer fabrics and their combination can improve the sound absorbability.

Chen and Long still work on the understanding of the absorption coefficient of warp-knitted spacer fabrics with different structural parameters including inclination degree of spacer yarn, thickness, surface layer structure and diameter of spacer yarn [11]. The study demonstrates a particular interest in the changing of inclination degree of spacer yarn. The spacer fabric made with smaller inclination degree of spacer yarn has superior sound absorption abilities as compared to the corresponding fabric. In contrast, the fabrics produced by higher thickness and coarser spacer yarn exhibit preferable sound absorption performance. Furthermore, the fabric conducted of closer surface layer possesses better sound absorbability when compared to the corresponding fabric.

Sancak's research shows the potentialities of weft knitted spacer fabrics as alternative to the limitations of nonwoven fabrics. The research explores mainly the relationship between the acoustic absorption and the connection angles between the two horizontal layers. Higher thickness and density bring to higher absorption coefficient meanwhile, thinner samples with lower density have lower absorption coefficient. [12]. The author explains that one possible reason is that when the connecting yarn angle increases, the thickness of the fabrics also increases. It can thus be suggested that the yarn connecting angle and the linear density of the yarn could be the major factors for the fabric thickness, and also a strong link may exist between the fabric thickness and the sound absorption.

In 2017, Chen et al. work again on warp-knitted spacer fabrics after the research published in 2015. Respect to the previous work, they examined the relationship between polyurethane-based warp-knitted spacer fabric composites. Findings show that the composites possess promising acoustical damping performance due to their special structure, especially at the sound wave frequency lower than 3000 Hz. Furthermore, the sound absorption properties of composites are significantly affected by the fabric structural parameters, indicating that the variation of fabric structural parameters could be an approach to adjust the sound absorption properties of composites to meet the specific end-use applications. The idea to explore the behaviour of polyurethane-based foam composites is topic of Wang et al paper [13] the research shows that the reinforcement gives a important improvement of acoustic absorption. That is due sound waves enter the cells and interact with air to strengthen the thermal viscosity, thereby improving the sound.

Arumugam spent part of his scientific speculation on acoustic performance of spacer fabrics. In 2018, he explored the both thermal and acoustic performance.[14]. Due to to porous nature, interconnected pores, bulkier and 3D structure, the spacer fabrics have ability to attenuate more sound energy than the conventional materials. He measured the performance of six several warp spacers with different density, thickness, density and porosity. The research demonstrated that sound absorption increases with the reduction of the porosity. It is also found the linear regression correlation between the fabric properties. Instrumental and acceptable positive correlation between thermal conductivity and Noise reduction coefficient were found. It seems that the Thermal conductivity increases with increase in NRC.

In 2019, Arumugam et al. Compared 12 several warp knitted spacer fabrics with different density (from 127.42 to 335.47 Kg.m^{-3}), porosity (from 82.74 % to 90.74%) and thickness (from 1.5 to 3.5 mm). the application of a two-way ANOVA methodology to process the information, the research demonstrates that the density and surface layer structure of warp knitted spacer fabric results are highly significant on the above-mentioned fabric compression properties. Even minor changes in the fabric densities results in significant impact on the flow resistivity and NRC [15]. In last year's several research are developed aimed at understating the combination of knitted process to improve the performance.

In 2020, Abedkarimi et al. developed a computational analysis to forecast the acoustic characteristics of warp-knitted spacers based on experimental measurements. [16]

In 2021, Zheng et al, explored thermal and sound-absorbing performance of ultra-light 3d space [17]. In 2022, Farahani et al, studied the sound absorption enhancement with nanofiber [18]. Fu et al. studied a series of wet knit spacer fabrics with different structural parameters were fabricated, and the measured and predicted sound absorption coefficients were also compared. The results showed that the airflow resistivity was mainly determined by their density, thickness, porosity, and yarn arrangement. The sound absorption coefficient of samples can be enhanced with the increasing thickness and airflow resistivity, and the absorption tendency of double layer spacer fabrics assembled by samples with more yarns is coincident to those, and the coefficients were higher than 0.5 above 1000 Hz and higher than 0.8 above 2000 Hz..[19]. Nazan et al. developed a hybrif layerd structures base on natural fabric reinforces composites and warp knitted spacer for acoustic applications. The integration of natural fabric reinforced composites with warp knitted spacer fabric had better sound absorption performance compared to the glass fabric reinforced composites, and they were considered to have the potential of being used in interior noise control mainly in vehicles and buildings.

The gathered information and results of the aforementioned papers are aggregated in Figure 8. Among the initial 25 papers, the authors were able to be accessed to 10 papers.

4. RESULTS AND CORRELATIONS

The Fig. 8 demonstrates that besides thickness, porosity, composition, yarns etc. the 3D spacer fabrics have a high performance from 2000 onwards. The comparison with the current acoustic material demonstrates that 3d spacer fabrics have lower performance at low-middle frequencies.

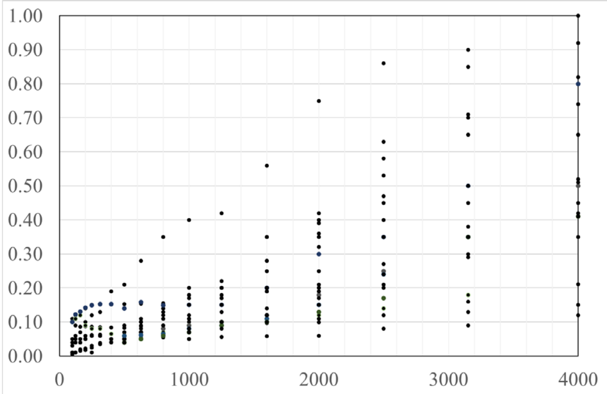

Figure 8. Aggregation of coefficients absorption of the papers quoted in paragraph 3.3.

5. CONCLUSIONS

The paper highlights the growing interest in research on the acoustic performance of 3d spacer fabrics. For this reason, the purpose of the paper to gather the research on this topic and provide a comparison between them. Among the several acoustic characteristics, the absorption coefficients behaviour is explored. Only published case studies are taken in considerations. The comparison aims to understand the behaviour of acoustic 3d spacer with common acoustic materials and acoustic textile and then the main characteristics features that affect the performance. Warp-knitted spacer fabric exhibits the typical sound absorption behaviour of microperforated panel. At higher frequencies, the noise actuation coefficients (NACs) of the warp-knitted spacer fabrics backed with weft knitted fabrics are much higher than those of the weft-knitted spacer fabrics backed with warp-knitted fabrics. The possibilities to combine several pattern and pile texture allow to programme the final behaviour according with the acoustic requirements of the space. Some limitations are presented. To have a deep understanding of the potentialities of these materials at architectural scale, an example of coefficient absorption measured in random incidence conditions has to be provide. Moreover, since the necessity to simulate the behaviour at digital environment is needed for architectural purposes, a reliable algorithm has to be implemented.

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