This is the accepted version of the publication, Hu Z, Zayed T, Cheng L., A critical review of acoustic modeling and research on building façade, Building Acoustics (2022;29(1)) pp. 107-134. Copyright © 2021 The Author(s). DOI: 10.1177/1351010X211022736.

A Critical Review of Acoustic Modeling and Research on Building Façade

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ABSTRACT

Noise pollution has been impacting negatively on living comfort and working environment for a long time. Acoustic treatment on building façade is one of the effective means to tackle this issue. Numerous articles were published over the past decades to address the acoustic related problems of building façade. However, a systematic review of the research development on façade acoustic technology is lacking. Therefore, this paper examines the published research articles from seven selected journals, in terms of the annual number of articles, citation counts, co-authorships, research locations, and keywords. The analyses show that interest in façade acoustics increased during the last two decades. Researchers from Europe and areas with a high density of tall buildings made significant contributions to this development. Based on keyword analysis, articles are categorized into three groups. These include sound insulation studies, studies on the effect of façade on street noise, and noise reduction techniques. The surveyed research topics comprise numerical modeling, experimental studies, ISO standard development, and analyses on annoyance level. Potential future directions are presented based on a summary of the limitations of the existing research. This paper offers researchers and engineers an in-depth understanding of the state-of-the-art of the current façade acoustic research. Additionally, potential future directions are identified based on the findings and limitations of the previous studies.

Keywords: research review; building façade; façade acoustics; research trend; sound insulation; noise reduction

1. INTRODUCTION

A façade is the exterior side, especially the face, of a building. The building façade system generally includes two parts: the structural elements to resist movements and the envelope elements to separate the inside and the outside environments. The functions of a façade are multifaceted. It minimizes the influence of rain and wind, helps in controlling light levels from the outside, and controls air permeability, thermal and acoustic insulations, etc. Because building facades are expected to sustain wind actions and transfer them to the main building structure, connections are mounted on each floor so that the building frame supports the weight of the building façade of the floor above it. The façade may either be bottom-fixed or suspended from the floor above. For office use buildings, large areas of glazing from floor to ceiling are required to provide a sufficient level of natural light. A greater expanse of glazing can enhance the penetration of direct sunlight into a building, which leads to solar gain and glare. A good design of the building façade should guarantee that all these functions are at an acceptable level [1].

Recent advances in building façade focused more on the incentive of sustainable development [2-6]. A typical example is the Double Skin Façade (DSF) system, which was innovated and widely deployed in European countries. Considerable thermal performance was achieved in both cold and warm seasons when the ventilation strategies of the DSF system were optimized. However, the realization of acoustic insulation becomes more difficult when a complex ventilation system was deployed. This could lead to an increased sound transmission through the internal structures among different floors. A similar challenge could be encountered when a larger glazing is used for the solar gain purpose.

The environmental noise problem is becoming increasingly serious. Environmental indicator report by the European Environment Agency [7] indicated that efforts to control environmental noise appeared to be offset by an increase in the number of people exposed to a high noise level. Therefore, researchers paid significant attention to the effect of a building façade due to its key role in the transmission and reflection of environmental noise.

Relevant studies began in the 1970s. Examples include prediction of the level of sound pressure transmitted through a balcony façade into a room [8] and investigation of sound propagation in a street of façade boundaries [9]. Since then, numerous works were also published to investigate the sound insulation performance and surface reflection characteristics of the building facade. The research objectives ranged from acoustic modeling to the improvement of noise reduction ability, and many other relevant topics. According to the analyses of the existing literature, academic interest in this area is growing fast. A systematic classification and review of the previous publications will considerably benefit future researches in this area.

It is widely accepted by the research community that a good literature review plays an active part in examining the extent of research on a specific subject. A study showed that a systematical review can not only assist researchers in developing insights into a topic but also inspire them on new directions to avoid duplicating past efforts [10].

Despite the significance of a research review, no such work has been directed at façade acoustics. Therefore, this paper conducts a systematic analysis and review of the articles published in the façade acoustic area. The objectives of this paper are 1) to adopt a bibliometric study to identify the latest and popular research topics in façade acoustics; 2) to present an overview of each research topic pertinent to façade acoustics; 3) to reveal the current limitations in façade acoustics with the aim of providing suggestions for future research.

2. RESEARCH METHODOLOGY

The review methods used in some previous researches [11-13], which belonged to either construction engineering or acoustics, offered valuable guidance for the work in this paper. In this paper, the Scopus search engine is used to identify the relevant articles. The keywords used in this search engine are *façade* and *acoustic*. Articles containing these terms in the title, abstract, or keywords are selected for this review. The search is further narrowed to cover only English publications including those published in journals and conference proceedings.

It was found that seven journals, namely, Applied Acoustics (AA), Journal of the Acoustical Society of America (JASA), Building and Environment (BE), Building Acoustics (BA), Journal of Sound and Vibration (JSV), Noise Control Engineering Journal (NCEJ), and Acta Acustica United with Acustica (AAUA) published at least 10 façade acoustic related articles. Therefore, a total of 7 academic journals were used in the review analysis of façade acoustics. Following the selection criteria above, 199 articles published in the 7 selected journals between 1990 and 2020 were retrieved for the review.

3. DATA ANALYSES AND DISCUSSIONS

3.1 Qualitative Analyses

Figure 1 shows the number of papers published per year on façade acoustics. Interest in the discipline of façade acoustics becomes pronounced from the 1990s and it has continued to increase significantly. Nineteen articles were published in 2015. The data of year 2020 is cut-off in August. This trend indicates the increasing amount of attention that the façade acoustics receive from researchers. To better analyze the variation trend in the last two decades, the number of papers published per year in each journal is shown in Fig. 2. Table 1 shows the annual number of published papers that are related to façade acoustics in the 7 selected journals. A significant increase can be observed in the last few years for acoustic engineering applications (AA and BE) and building applications (BA).

Table 2 lists the highly cited top 10 papers for reference. Notice that the effect of publication year on the citation number is not considered. The list shows that the most cited papers fall into the noise abatement category. This category explores the potentials of green roofs in reducing sound transmission over the façade surface. In Table 2, four articles focus on noise control techniques and five on acoustic modeling. These two topics are intensely investigated by scholars of façade acoustics.

Table 3 lists the number of citations of the selected journals in terms of façade acoustics. It is found that AA is the most-cited journal. However, in terms of the number of times an article is cited, JASA, BE, and JSV score more than AA. Particular attention should be paid to JSV, which has the most cited times per article out of the 7 selected journals. However, the number of articles on façade acoustics in JSV is the second lowest among the selected journals. The good performance of JSV can be attributed to the scopes of JSV, which emphasizes fundamental works with the potential for practical applications. Basically, within the area of façade acoustic, fundamental research has a larger chance to be cited by other related works.

3.2 Science Mapping Analyses

The above filtered 199 articles are analyzed with *VOSviewer*, which is a software tool for constructing and visualizing bibliometric networks. The research co-authorship, research country locations, and co-occurrence of keywords are studied.

Awareness of the existing scientific collaboration networks in any field of research facilitates access to funds, specialties, and expertise. It also enhances productivity and assists investigators to reduce isolation [14]. Here, the minimum number of publications and the minimum number of citations are set to 2 and 10, respectively to extract information on authorship. As a result, 71 out of a total of 376 authors are identified from the co-authorship analysis. The first two clusters among these collaborations in façade acoustics are shown in Fig. 2a. The second group mainly focuses on the performance and characterization of vegetation as a noise control device and the effect of traffic noise in a street canyon with building façade.

Countries are also analyzed for their contributions to façade acoustics. Figure 2b shows the mapping of façade acoustics studies in terms of the country locations of the scholars. The minimum number of publications and citations are set to 5 and 20 respectively in *VOSviewer*, resulting in 18 out of a total of 42 countries being selected. It can be seen in Fig. 2b that most countries active in façade acoustics are in Europe. Particularly, the five countries in the core of co-authorship, France, Italy, the United Kingdom, Netherland, and Belgium, are all European countries. Additionally, they are more likely to cite each other's work as shown by the line thickness. This can be attributed to the widespread use of façade, such as DSF, which has been deployed in more than half of countries in Europe in the year 2016 [15]. Another characteristic of the façade acoustic study location is the high density of tall buildings in places like Hong Kong, which is constantly suffering from street traffic noise.

Keywords play an important role in a research article because they represent the essential contents of an article and summarize the topics studied within a given discipline [16]. The co-occurrence of keywords is analyzed. Among the 199 selected articles, "Author Keywords" and "Fractional Counting" were set in *VOSviewer*, as suggested by Hosseini et al. [14]. The software initially outputted 24 out of 323 keywords. Next, the inclusion and exclusion of keywords were manually conducted based on the following rules: (1) minimum number of occurrences of a keyword was set to 3; (2) general keywords, such as "façade", "acoustic", and "building" were removed; and (3) keywords with essentially consistent meaning were combined, for example, "sound insulation" and "acoustic insulation". Finally, the co-occurrence of the remaining 15 keywords are shown in Fig. 2c.

It is found that "environmental noise" is the most mentioned keyword. This is because it is the most prevalent source of noise in façade acoustic studies. There are several other major keywords, i.e. topics, which are closely linked to "environmental noise". Sound insulation refers to the acoustic transmissibility of the façade. It is worth noting that there is a keyword that is strongly connected to sound insulation, the "ISO 140-5". Although ISO 140-5 has been updated to ISO 16283-3 since 2014, existing researches towards ISO 140-5 can still provide a valuable guidance for the new comers in this area. This keyword represents the field measurements of airborne sound insulation of façades. This series of ISO standards play a significant role in evaluating and examining the acoustic performance of a designed façade.

"Noise reduction" is another major topic in façade acoustics. It indicates that façades are not only being used for increasing insulation to control the indoor noise, but also for reducing the noise level in the street. Particular attention should be paid to keywords, like "noise mapping", "reflection", and "sound propagation", with which most works study the effect of façade on street canyon noise. These keywords are not well reflected in Fig. 2c because they do not tend to be listed as a keywords by the authors. Another misunderstood or underestimated keyword is "numerical modeling", which is of significant importance in façade acoustic studies. It is applied in the predictions of sound insulation ability, noise reduction performance and sound propagation in urban space, etc.

Following the analysis shown in Fig. 2c, the technical review part in this paper will be categorized into three sections. The first part is on sound insulation and acoustic characteristic of the façade itself. It also includes the effect of a building façade on the indoor sound environment and subjective annoyance level. Next is the effect of building façade on the outdoor environment, which refers to the sound propagation and street canyon noise. Lastly, noise reduction, either aimed at an indoor or outdoor environment, will be summarized as an individual section.

4. Studies on Sound Insulation of Building Façade

The studies on the sound insulation properties of building façade mainly focus on the prediction and evaluation of the sound insulation ability. One way is to find a specific approach, either numerical or experimental, to predict or assess the acoustic characteristic of a given façade structure. The other is to follow the ISO standard to measure the sound reduction index of a façade. Efforts have been devoted to the improvement and future development of the corresponding ISO standard. In addition to the prediction and measurement of the Sound Reduction Index (SRI) of a façade, the effect of the façade on the resident annoyance level is also an attractive research direction.

4.1 Evaluation of Acoustic Characteristics

Evaluating the acoustic characteristics of a building façade is of great importance in terms of design and other practical applications. The evaluations can be conducted either numerically [17-37] or experimentally [15, 38-64].

4.1.1 Numerical Methods

To study the acoustic characteristics of a given facade, numerical tools, such as the Finite Element Method (FEM), used in traditional vibroacoustics are generally applied. For example, Arjunan et al. develop a 2D FEM to predict the SRI of a stud-based double leaf wall of a finite size [17]. Despite the insightful analyses, it is recognized that the extension of the method to 3D analyses is difficult due to the large number of elements needed. In fact, the rule of thumb stipulates that at least 8-10 elements per wavelength are usually required to obtain converged and reliable results [17]. This reflects the difficulty in modeling a building façade due to the large dimensions and complex components in different façade layers.

However, traditional numerical modeling approaches usually require enormous computational resources. To overcome these challenges, researchers choose to adapt the existing vibroacoustic models, such as the Transfer Matrix Method (TMM) and Finite-Difference Time-Domain (FDTD) analysis. These are used to target the structures or develop specific models based on a general framework, such as the Artificial Neural Network (ANN). For example, the External Thermal Insulation Composite System (ETICS) [18] is commonly used nowadays to increase both thermal and acoustic performance of a façade. However, traditional sound transmission models are not accurate enough to analyze the partitions in ETICS. For example, the TMM is usually employed in predicting the acoustic transmission of a multilayer structure, which is a multilayer façade in the present case, as shown in Fig. 3a. The general formulation of the system in Fig. 3a can be described by

$$\mathbf{V}^{S1} = [\mathbf{T}]\mathbf{V}^{S2}, \tag{1}$$

where V^{S1} and V^{S2} are the vectors to define the acoustic field on surface S1 and S2, respectively, and **T** is the transfer matrix whose size depends on the nature of each layer as solid or poroelastic. The basic assumption of this method is that the dimension of each layer is infinite in the lateral direction, i.e. y-axis in Fig. 3a. Therefore, the error of TMM is significant, especially within the low-frequency range due to the structure modes of the finite size layers. Santoni et al. [18] developed a numerical model based on the TMM, which adds correction factors to address these assumptions. The ratio between the average velocity on surfaces S_1 and S_2, as marked in Fig. 3a, were calculated by the TMM. The results are shown in Fig. 3b. It can be observed that the model shows good agreement with the experimental data in the low-frequency range, while the results in higher frequencies are overestimated. This can be attributed to the influence of uncertainties. Also with the TMM, Attal et al. [33] simulated the absorption coefficient and effective acoustic properties of a multi-layer green façade. The effects of the plant, soil, and air gap thickness were also taken into account to improve the absorption bandwidth. Asakura and Sakamoto [34] presented a numerical method to predict the sound insulation performance of a façade wall system using the FDTD analysis. The sound transmission loss of glass plates and plasterboard walls was obtained with the proposed model. The energy loss at the boundary part of the plates and the internal damping of the plates were taken into account in the prediction model. Later on, this model was applied to predict the sound from passing vehicles transmitting through a building façade [25]. As a further application of this model, a 2-D to 3-D

Fourier-like transformation technique has been developed to improve the modeling efficiency [19]. With the improved method, more elements can be included in the model. Eaves and louvers attached to the building façade were found to be effective for noise reduction. Based on a previously developed piecewise modeling scheme [65], Hu, Maxit, and Cheng present a tool for systematical design and analysis of building façade in mid-to-high frequency range [37]. It is shown that besides the prediction of sound insulation characteristics, the proposed piecewise scheme can be more comprehensive when compared with traditional modeling tools to achieve complex functions like sound intensity mapping and boundary absorption evaluation in a shorter period.

Other research efforts include the application of the ray theory. Li and Tang [30] developed a ray model to study the sound reflections between the barriers in front of a tall building and the façade surfaces. The predictions of the model were proven to agree well with the in-door measurement over a broad frequency band. Hossam El Dien and Woloszyn [27] conducted a pyramid ray-tracing simulation to study the effect of the balcony depth on the noise protection level of a façade. A total of 0.5 – 8 dB(A) noise reduction could be achieved, throughout the investigated configurations. Prediction results showed a good agreement with the measured one.

Besides the traditional modeling methods in vibroacoustics, ANN has also been employed by researchers. Buratti, Barelli, and Moretti [24] developed an ANN-based model to evaluate the sound insulation performance of a wooden window façade. The system had five main parameters as network inputs, which are window topology, frame and shutters thickness, number of gaskets, and sound insulation index of glazing. The sound insulation index R_w of the window, according to EN ISO 717-1 [66], was the output of the system. The networks were trained under different configurations and a root-mean-square error of less than 3% was obtained. The results are shown in Fig. 4. A good agreement can be observed for both windows and French windows. These results show that the system can be very useful for the acoustic design and optimization of new products.

4.1.2 Experimental Methods

Experimental methods are friendly to solving problems with a strong practical background like a building façade. Because the reliability of numerical methods is limited by numerous uncertainties, experimental methods can be used to improve the modeling performance. Some researches opted to study the acoustic characteristics of a façade in laboratories [15, 38-53]. Díaz and Pedrero [38, 39] experimentally investigated the effect of rolling shutters and shutter boxes on the sound insulation properties of a façade window. The study contained a summary of sound insulation from airborne noise in several types of windows with a built-in shutter and prefabricated box. The effects of different shutter arrangement, shutter box material, and noise spectrum on the sound insulation ability were given.

Some other experimental studies were aimed at summarizing an empirical formula to describe the complex acoustic characteristics with a few parameters. Urbán et al. [15] experimentally analyzed the sound insulation ability of 18 different DFS with the test configuration shown in Fig. 5a. Parametric studies were conducted on cavity thickness, absorptivity of the cavity, effect of the size of ventilation slots, etc. Additionally, a mathematical formula was proposed to estimate the sound insulation ability of the DSF, as

$$D_{2m,nT} = R + 10\lg\frac{0.32V}{S}, \quad (2)$$

in which $D_{2m,nT}$ is the standardized level difference, V is the volume of the receiving room, S is the area of the examined façade sample, and R is a function of frequencies, structural dimensions, and material properties. The predicted results were verified by the measured ones, as shown in Fig. 5b. Detailed structures of each DSF system can be found in Ref. [15]. It can be seen that the proposed model generally outperforms the one previously proposed by Blasco [67].

On the other hand, owing to the large dimensions of the façade structure, some researchers have chosen to use scaled configurations to facilitate the tests. Tang et al. [40] experimentally studied the insertion loss of asymmetrical balconies on a building façade with a 1:3 scaled-down model. It was shown that the position of the sound source relative to the full-height sidewall significantly affects the balcony insertion loss. For short side-wall structures, the insertion loss spectral pattern was determined, where coupled modes can be observed so that sounds are amplified at these frequencies regardless of balcony form and elevation angle.

To take the actual noise environment into account, some studies directly measure the acoustic performance of a façade on-site to make the results more reliable [54-63]. For example, field measurements have been carried out to investigate the façade sound insulation ability of balcony windows [54]. The measurements were taken with the guidance in ISO 140-5 and the Single Number Quantities (SNQ) was analyzed accordingly. It was shown that the SNQ for sound insulation varies as the test methods, noise sources, or changes in the angles of incidence, even if the tested façade configuration is identical. Therefore, it was suggested that the field test results of a product should be given together with the method and environment of measurement. School is a typical site which has a rigorous requirement in terms of the acoustic environment. Secchi et al. [55] investigated the effect of traffic noise and façade insulation on the indoor acoustic environment with a sample of 103 facades from 54 different school buildings. Measurements were conducted both before and after adding acoustic treatments to the façade. The obtained results showed that the indoor sound pressure level was significantly attenuated after improving the façade insulation ability.

Researchers have also tried to improve the testing technologies to obtain improved results. To study the infrasound insulation ability of a façade, Keränen, Hakala, and Hongisto [64] designed a special infrasound loudspeaker. The frequency range of the loudspeaker was as low as 5 Hz and it was exploited to measure the outdoor-indoor level difference of 26 different façades. Other standard methods to measure the sound reduction index (SRI) of a façade were down to 50 Hz only.

4.2 Studies on ISO Standards

ISO standards play an important role in the engineering field since they ensure the quality of designed products. As for the acoustic design of building façades, the ISO standards are applied to guarantee the insulation ability, reliability of measurement, etc.

Studies have been conducted to improve or assist in the future development of the ISO standards [68-78]. An interesting point is although some papers are targeted to the withdrawn standard ISO 140-5, which has been replaced by ISO 16283-3, their conclusions are still valid. Revisions made in the new standard can be referred to in Berardi's work [79]. A study has investigated the influence of the front microphone mounting condition towards improving ISO 1996-2:2008 standard [78]. Results indicate that the traditional correction factor may lead to significant errors in the results collected over a long duration, such as monthly based. The study proposes that the correction factor should be determined case-by-case. Besides, it further advises that *in-situ* studies are necessary when precision measurements are needed.

Some evaluations have also been conducted with respect to the development of future standards regulating road-traffic noise. In this regard, Hongisto et al. [77] evaluated 25 different SNQs correlated with subjective ratings of road-traffic noise transmitting through a façade. Five spectrally different traffic noise and 12 façade structures, i.e. 60 combinations, have been evaluated in a psychoacoustic laboratory in total. The study suggested the most suitable SNQ for the standard road-traffic spectrum of ISO 717-1, which can benefit the development of future standards.

Another factor that has a significant influence on the performance of modeling and measurement is the uncertainty effect. Navacerrada et al. [71] have conducted a series of analyses on the uncertainty values mentioned in the standard ISO 12999-1. These values were summarized from interlaboratory activities and individual calculations. The comparisons were based on around 1000 *in-situ* measurements for sound insulation.

The study showed that the Monte Carlo simulation is an acceptable method if an estimation of the uncertainty effect is needed.

4.3 Studies on Annoyance Level

Researches on annoyance evaluation have been conducted [80-89]. Some study the effect of building façade on the noise annoyance level in general. In a laboratory, Ryu and Song [80] experimentally investigated the effect of building façade on traffic noise annoyance in terms of frequencies and sound insulation ability. The relationship between the subjective annoyance level and the noise spectrum was studied. It was shown that the proper use of a building façade can considerably reduce the annoyance level. The on-site survey questionnaire is also an effective way to study the noise annoyance level in a certain area. A survey investigation [81], which features 18 areas from two cities in Norway and a total of near 4000 respondents, reported that a single glazing window with poor insulation ability can lead to a higher noise annoyance level.

5. STUDIES ON STREET CANYON NOISE

Similar to the studies on sound insulation properties, researches on the effect of building façade on street canyon noise can also be divided into numerical studies [90-114] and experimental studies [115-119].

5.1 Numerical Studies

There are two major objectives when investigating the effect of building façade on street canyon noise; one is the sound propagation process and the other is the noise mapping.

5.1.1 Modelling of Sound Propagations

The effect of building façades on street canyon noise is another hot topic in the façade acoustic area. One of the most representative methods is the Boundary Element Method (BEM). This technique is friendly to large-space acoustic simulations with given boundaries [90-92], although such a low-frequency method usually requires tremendous computational resources and time when the dimensions of the modeling target become larger.

A BEM based model [92] was proposed by Salomons et al. to study the multiple reflections by building façades in street canyons. The method was supported by a room-acoustical analysis of the reverberant sound fields in the source and receiver canyons. Noise maps and exposure distributions of the city of Amsterdam were generated. The model helped to redistribute traffic flows to reduce the percentage of highly annoyed inhabitants from 23% to 18%. Montes González et al. [90] have also numerically studied the effect of vehicle parking lines on the noise over a building façade with BEM. A screen effect was observed with the presence of the parking line, which was suggested to be considered in the future noise mapping projects.

Owing to the development of the Perfectly Matched Layer (PML), the Finite Element Method (FEM) can also deal with an infinite domain by truncating it into a finite processible one. Pelat et al.[98] proposed a coupled modal-finite element method to model wave propagation in a street canyon. The multiple reflections of the acoustic waves on the building façades were taken into account. This allowed the acoustic field to be modeled as an irregular open waveguide. Although the model revealed the acoustic wave propagation mechanisms along a street, the obtained result was rough in terms of boundary conditions.

To take more boundary details into account, Echevarria Sanchez et al. [94] numerically studied the sound pressure level distribution with a full-wave FDTD analysis. They demonstrated in detail the strong effect of building shape, street geometry, and the presence of street furniture on people's noise exposure. Finally, the immission levels (L_p) are obtained for different octave bands as

$$L_p = L_w + relSPL - Aff, \tag{3}$$

where *relSPL* is the acoustic energy expressed relative to the free field, *Aff* is the attenuation observed in the free field, and L_w is obtained from the CNOSSOS (Common Noise Assessment Methods in Europe) Equivalent source model [120]. It was found that a proper façade design could reduce the average noise exposure at windows by 12.9 dB(A). Also based on the FDTD analysis, Van Renterghem, et al. [99] proposed an FDTD-PE (Parabolic Equation) method to increase the modeling efficiency and to reduce the required computational cost. The FDTD-PE model explored the symmetry of the source and the receiver canyon. With the proposed calculation method, simulations are only necessary for half of the sound propagation domain.

5.1.2 Sound Field and Noise Mapping

Geometrical acoustic-based ray theory is another popular tool used in large-space acoustic modeling [108-114]. A typical example is the sound field prediction and noise mapping in urban space. A radiosity-based numerical model has been proposed by Kang [108], as shown in Fig. 6a. The model studies the fundamental characteristics of the acoustic field in an urban street resulting from diffusely reflecting boundaries. The model divides the boundaries of a street into a set of patches. Then, the sound energy response at receiver $R(R_x,\ R_y,\ R_z)$ is given as a function of time and represented as

$$L(t) = 10\lg\left\{E_d(t) + \sum_{k=1}^{\infty}[E_k(t)_G + E_k(t)_A + E_k(t)_B]\right\} - L_{ref}, \tag{4}$$

where $E_d(t)$ is the direct sound, L_{ref} is the reference level, $E_k(t)_G$ is the energy contribution from each patch source being considered, and $E_k(t)_A$ and $E_k(t)_b$ are the energy contributions from the patches on façade A and B, respectively. A set of calculations of the SPL distribution is shown in Fig. 6b. It can be observed that SPL variation along a street can be well described by the proposed model. The work emphasizes the effect of the reflective property of the street ground on a diffusively reflective façade. In other words, if building façades are diffusely reflective, the reflective property (diffusely or geometrically) of the street ground has no significant effect on the sound field distribution within the street.

Similar to Kang's method [108], another study reported the acoustic characteristics in urban squares surrounded by a reflective building façade [109]. The effects of façade design on reverberation time and sound pressure level reduction were investigated.

These investigations include the reflection pattern, height, aspect ratio, boundary absorptions, etc. However, when modeling the façade reflections and the corresponding fittings, the required computational resource and time significantly increase. To save modeling cost, Can et al [110] ran 32175 simulations to quantify the errors of neglecting acoustic diffusion by the façade. Thereafter, the authors applied regressions to evaluate the impact of diffusive reflections and street fittings on sound propagation. These regressions can be used to refine sound levels predictions when using classical outdoor sound propagation models without considering the effect of façade reflections. Some other researchers also focused on noise sources other than traffic noise. Riegel and Sparrow [111] proposed a combined ray tracing/radiosity method to model the sound field of sonic booms around buildings. The influences of façade features, absorption coefficients, and scattering coefficients were investigated. The calculated results were in good agreement with the measured ones.

5.2 Experimental Studies

Scaled-down models are often used to study road traffic noise due to the on-site measurement difficulties [115-118]. Compared to a full-scale on-site test, most parameters can be optionally controlled and studied, and the uncertainties level can be reduced [116]. With a 1:50 scaled-down model, Picaut and Simon [115] studied the effect of multiple reflections and diffuse-scattering by façade irregularities on sound propagation in a street. The results of the scaled model were compared with the on-site measured ones. It was found that the attenuation effect can be well predicted with the scaled model. However, the sound level in the scaled model was found to be generally lower when the receiver is away from the source. It was then suggested that a larger scale factor should be used. In the model of Hornikx and Forssén [116], facades of acoustically rigid, absorptive, and diffusive surfaces were investigated. The analyses included sound pressure level, decay time, and 3-D geometrical effect in a street canyon. Besides, a wavelet-based method was applied to correct the air attenuation effect.

On the other hand, on-site experimental studies usually involve more complexities so that more dedicated techniques are required. For instance, Bjelić *et al* [119] designed a microphone array system to analyze the characteristics of traffic noise. Notably, the system contains a lower number of microphones compared to existing solutions. The designed system was dedicated to the analysis of the angular distribution of incident sound energy impeding a facade in the urban environment.

6. NOISE REDUCTION TECHNIQUES

The noise reduction method is also a hot topic. The ultimate objective of investigating façade acoustics is to improve the indoor and outdoor acoustic environment. Generally, noise reduction techniques in façade acoustics include using absorptive materials [121-128], adding control components [129-131], applying new designs [128, 132-136], etc.

To reduce the noise level close to a building façade, one straight forward way is to add a layer of absorption material over the façade surface. For instance, Wang *et al* [121] numerically investigated the effect of the phase gradient of the façade ceiling surface on screening exterior noise with a ray-based model. It was shown that, with impedance inhomogeneity being used on the ceiling surface, the sound reflections were considerably reduced, particularly in the high-frequency range. However, the absorption material has a durability problem when exposed to the environment on a building façade surface in a long-lasting application scenario.

To tackle this issue, Ishizuka and Fujiwara [124, 125] proposed a ceiling-mounted noise reflector to achieve the noise-shielding effect. The performance was experimentally assessed for balconies with ceiling-mounted reflectors on a high-rise building façade. The sound pressure reduction, provided by the reflectors, on a window surface adjacent to the balcony was evaluated at intermediate floor levels. The design was examined in a full-scale balcony for practical use.

Active control is another popular technique in the noise control society [127, 129]. Aiming at reducing the noise of an aircraft fly-over, Pàmies *et al* [129] designed an active control system for sound transmission through a restricted opening bottom-hinged window. A 3dB of transmission loss increase was achieved in the low-frequency range.

Applying a new design is also a preferable selection. Hossam El Dien and Woloszyn [27] modified the angle of the ceiling surface within the balcony. An additional 0.5 – 6 dB noise reduction was achieved according to the proposed numerical model. Jessop et al.[130] also investigated the effect of adding non-periodic stiffening elements to windows for impaired sound transmission. The results show that the low-frequency sound transmission loss below 150 Hz can be increased by several dB. Santoni et al. [135] investigated the possibility of using Wood Plastic Composite (WPC) as a façade cladding or sound barrier. The proposed configuration showed good potential in roadside buildings.

In addition, Yu [131] proposed a new design of acoustic metasurface to improve the sound insulation of a building façade structure. The parameters were tuned based on FEM, while *in-situ* measurements were taken to test the performance. The design was shown to outperform the traditional casement window by 7 dB in terms of SNQ noise rating. Badino *et al* [132] also investigated the effect of façade shape and acoustic cladding on the reduction of noise levels in a street canyon. It was shown that the noise reductions achieved were much higher than those by increasing the sound absorption of the street paving. This study highlights the role of façade design in environmental noise mitigation.

Among existing noise control techniques in building façade, the utilization of vegetation has become popular in the last decade [137-144]. Such a disposition can simultaneously improve the thermal and acoustical performance environmentally. Renterghem and Botteldooren [141] explored the potential of green roofs as a control device to reduce the effect of road traffic noise loading on a façade. The effects of traffic speed and vehicle types on the performance of the green roof were parametrically studied. One of the analyzed sets is shown in Fig. 7. For a detailed parametric arrangement, readers can refer to Ref. [141]. It can be observed that most of the green roofs can achieve an approximately 5 dB reduction on the sound pressure level at the relatively low height region. It is also shown that the shielding of a green roof can be achieved when its parameters can be properly tuned.

Pérez *et al.* [137] experimentally examined the acoustic insulation of two Vertical Greenery Systems (VGS) *in-situ*. It was found that a thin layer of vegetation can introduce sound insulation between 1 and 3 dB, according to the subjected excitations. It was also suggested that the influence of other factors, such as mass related factors, type of modular unit, and support structures, should be considered in future design processes. Yang et al.[143] measured the random incidence absorption and scattering coefficients of vegetation. They considered various factors, such as soil depth, soil moisture content, and the level of vegetation coverage. It was shown that at higher frequencies, sound absorption and scattering become stronger as the vegetation coverage increases. Davis et al. [139] also measured the sound absorption properties of a vertical garden system in a building façade. Their study suggested a design by which the configurations of a vertical garden can be optimized to suit the target noise frequency spectrum.

7. RESEARCH GAPS AND LIMITATIONS

Despite the significant progress made in the study of the acoustics of a building façade as reviewed in previous sections, there are still limitations and space for future studies. Figure 8 lists some of these topics.

Firstly, some numerical studies aimed at predicting the acoustic characteristics of the building façade suffered from obvious inadequacy. Some numerical models have been developed based on empirical formulas, which are efficient and user-friendly. However, these models are too rough when compared with the actual experimental data. Furthermore, they can hardly address the need for allowing parameter variations at the design stage.

On the other hand, although more accurate modeling tools such as boundary element analysis and finite difference method exist, they are extremely and computationally cost-demanding. Therefore, they can hardly be used for optimization purposes. Potential solutions may be obtained from the mid-to-high frequency methods in vibroacoustic analyses, which combines computational accuracy and efficiency. Basically, the mid-to-high frequency methods can be categorized into the enhanced low-frequency methods [145-148], the enhanced high-frequency methods [149-151], and the hybrid methods[152, 153].

The use of ISO standards for the measurement of the performance of a façade also suffers from similar drawbacks. Although there are some ISO standards for this purpose, the test procedure produces a reference for comparison only. However, they cannot provide engineers with adequate analysis and optimization tools. The reason is that the ISO standard does not address the issue of the variation of noise performance as a function of design parameters and neglects the possible integration of noise control devices inside façades.

The effect of building façades on the annoyance level is important as a civil structure. Albeit the effect of building façade on noise annoyance level is still not completely understood, it would be better to address the annoyance consideration at the design stage based on the existing knowledge.

The limitations of numerical methods in street canyon noise studies are similar to those in sound insulation studies. It is difficult to balance the efficiency and the fineness of a method. Specific methods are needed to address this issue. For the experimental methods, scaled-down tests offer flexibility in terms of geometry size, reflection, and absorption. However, considerable discrepancies can still be observed when estimating high-frequency noise, where the atmosphere attenuation cannot be well apprehended in the scaled model. If the scaled ratio is large (e.g. more than 50), the acoustic similarity process becomes complex due to the use of ultrasonic sound sources, adapted receivers. For the on-site test, besides those less competitive compared with the scaled-down model, legal authorizations from city administrations and limitations in measurement duration exist. Uncertainties like abrupt noise and weather changes also bring additional challenges to the reliability of field measurement results.

Noise reduction is an attractive topic not only in façade acoustics but in many other acoustic branches, like structure acoustics and room acoustics. It is widely accepted that exploring its mechanisms and making parametric analysis can significantly benefit the optimization of control devices. Therefore, dedicated analyzing tools should be developed to increase the control performance of a typical device. A representative example is the Micro-Perforated Panel (MPP). As shown in the existing literature [154-156], the measured absorption coefficient of MPP cannot completely reflect its *in-situ* performance. This can result in false predictions in the induced noise reduction benefit. The MPP should be analyzed together with the façade structure as an integral part. In this respect, the investigations on vegetation wall and green roof provide a good example, as reviewed in Section 5. Such a methodology should be advocated and promoted in the development of other noise control devices. Additionally, with an analyzing tool, the control efficiency could be further improved by especially considering the frequency spectrum obtained from the annoyance analysis.

As a final remark, the authors summarize the potential directions for future researches in façade acoustics in the following. Firstly, there is a need for the development of an integrated tool that can facilitate the acoustic design and optimization of different façade configurations. Additionally, parametric studies with such a tool can take the annoyance analysis results into account. Not only can the design period be shortened, but the performance of the noise control devices be improved at the same time. This will benefit both the improvement of sound insulation and street noise reduction.

From experimental studies perspective, uncertainties should be better apprehended in the scaled-down tests to better mimic the practical environment, which can considerably strengthen the reliability of the results. Finally, although many investigations and surveys are conducted on the effect of a building façade on the annoyance level, most of them focus on sound insulation performance. Studies on the annoyance level in terms of street noise in urban spaces are scarce in the open literature. Such studies deserve more attention to benefit the research on building façade and street noise.

8. CONCLUSIONS

A comprehensive review of the studies on the acoustic effect of a building façade is presented. The review is conducted on research articles published in seven selected journals, namely, AA, JASA, BE, JSV, AAUA, BA, and NCEJ. It is found that the popularity of research on façade acoustics has been persistently increasing in the last two decades. Most researches are in Europe due to the wide application of façade technology. The central topic in façade acoustics is environmental noise, around which sound insulation and noise reduction are the two most attractive directions. Most of the other topics can be classified into studies on the effect of building façades on the street canyon noise. A systematic review of façade acoustics is presented based on the above three categories. Research limitations and existing gaps are identified and summarized following the reviews.

Generally, this study provides a reference for both academia and noise control engineers in buildings. It is relevant to note that, despite the effort in collecting the most representative articles to reflect the current statues of façade acoustic research, the cited references are in no way exclusive and it is an insurmountable task to include all existing papers. Readers are advised to read the paper in this context.

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