A combined sound field prediction method in small classrooms

Da Yang [a], Cheuk Ming Mak [a, *]

[a] *Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*

da.yang@connect.polyu.hk, cheuk-ming.mak@polyu.edu.hk

*Corresponding author.
E-mail Address: cheuk-ming.mak@polyu.edu.hk (C.M.Mak).
Telephone: +852 2766 5856
Fax: +852 2765 7198

Abstract

In this paper, a new combination method for sound field prediction is proposed. An optimization approach based on the genetic algorithm is employed for optimizing the transition frequency of the combined sound field prediction method in classrooms. The selected optimization approach can identify the optimal transition frequency so that the combined sound field prediction can obtain more efficient and accurate prediction results. The proposed combined sound field prediction method consists of a wave-based method and geometric acoustic methods that are separated by the transition frequency. In low frequency domain (below the transition frequency), the sound field is calculated by the finite element method (FEM), while a hybrid geometric acoustic method is employed in the high frequency domain (above the transition frequency). The proposed combined prediction models are validated by comparing them with previous results and experimental measurements. The optimization approach is illustrated by several examples and compared with traditional combination results. Compared to existed sound field prediction simulations in classrooms, the proposed combination methods take the sound field in low frequencies into account. The results demonstrate the effectiveness of the proposed model.

Keywords: combined prediction methods; genetic algorithm; optimization; transition frequency.

Practical applications: This study proposes a combined sound field prediction method separated by transition frequency. A genetic algorithm optimization method is employed for searching the optimal transition frequency. The outcomes of this paper are essential for acoustical designs and acoustical environmental assessments.

Introduction

Classrooms are essential places where most formal education takes place. High levels of acoustical quality are required in classrooms. Therefore, sound prediction methods are crucial to evaluate the acoustical environments as well as acoustical designs. Various acoustic modeling methods are available in building acoustics for predicting the acoustical environment of constructions [1-5]. The room acoustical simulations are commonly based on two main approaches, which are widely used in acoustical modeling based on acoustic wave propagation equation (wave-based method) and assumptions of geometrical acoustics (GA method). The wave-based methods discretize wave propagation equations into finite elements such as finite element methods (FEM), [6-7] boundary element methods (BEM), [8-9] and finite difference time domain methods (FDTD). [10-11] In principle, the wave-based methods can obtain the most accurate results by dividing enough discretized elements. However, with the increase in frequency, the number of elements increased, which led to a large number of computational costs. To avoid the high computational costs in high frequencies, geometrical acoustics methods were developed. Under the basic assumption that the wavelength of sound was neglected at high frequency, the sound wave was assumed to be propagated as sound rays. The geometrical acoustical methods were widely applied in predicting sound fields in large spaces. [12-17] However, when it comes to small rooms, geometrical acoustic prediction methods appear to be flawed due to the inherent negligence of important low frequency wave effects, such as standing waves, diffraction, and interference. While in small rooms, it is known that inherent simplifying assumptions made for geometric acoustic methods limit the applicable frequency range to frequencies higher than the Schroeder frequency. [18] Room acoustic simulation methods based on the two mentioned main approaches both had limitations in predicting acoustic characteristics. Therefore, some researchers attempt to combine the two approaches in room acoustic predicting. Wang et al. proposed a hybrid technique based on Finite difference time domain methods (FDTD) and ray tracing methods for site-specific modeling of indoor ratio wave propagation. [19] Summers et al. combined the Boundary Element Method (BEM) and geometrical acoustics to assess the accuracy of aurilazation. [20]Aretz proposed a combination method of Finite Element Methods (FEM) and ray tracing methods for simulating sound field in small rooms. [21]

The previous studies proposed a low linear pass and high pass filters approach to combine the wave-based methods and geometric methods. [20-21] While in these studies, the authors proposed the combination methods focused on the combination of the results generated with both simulation techniques. They used a straightforward approach for combining both simulation results consist of low-pass/high-pass filtering the FE/ray-based results, both at the Schroeder frequency, and then simply adding the filtered frequency responses. The combination methods in the mentioned studies were effective for combining wave-based and ray-based prediction modeling in a real room. However, the computation costs seem not to be considered in the suggested approaches. In order to develop a combination prediction model with the consideration of computation costs. We designed a genetic algorithm optimization method to search the optimal frequency, which was the transition frequency for separating the wave-based methods and geometric acoustic methods. The FEM methods were employed as wave-based methods for calculating the sound field in that frequency domain lower than the transition frequency. And hybrid geometric acoustic methods were employed in that frequency domain high than the transition frequency. Computation costs were the main criteria in the mentioned genetic algorithm optimization methods.

From the analysis of previous studies, it emerged that the following issues on the topic of combined sound field prediction methods in small classrooms still need to be tackled:

(1) The selection of optimal transition frequency to combine the wave-based and geometrical acoustic prediction methods should be studied.

(2) The validation experiments of the combined prediction methods should be verified.

This approach aims to identify the optimal transition frequency so as to propose simultaneously effective and accurate combination methods. It will be applied to the small classroom prediction simulation. In practice, applications of sound field predictions can provide the predicting level and spectral content of the sound in buildings, which are essential to acoustical design and acoustic environmental assessment.

Theory

Combination of wave-based method and the geometric acoustic method

In the current study, a combination method that is based on a wave-based method and geometric method is proposed. The aim to propose the combined model is to predict the sound field over the whole audible frequency range efficiently and accurately. With the increases in the frequency, the number of elements will be too large to cost much of computing time as well as memories. The wave-based method is more accurate at low frequencies. Comparing with the wave-based method, the geometric acoustic method saved more computing time and memories at mid-frequencies and high frequencies. In order to develop an efficient and accurate prediction method over the whole frequency domain. The separated calculation is a necessary approach for combining the two mentioned prediction methods. The two mention methods are separated by a transition frequency. The transition frequency limits the applicable frequency higher than the Schroeder frequency.

Schroeder and Kutturff proposed a crossover frequency (Schroeder frequency) that marked the transition from the individual, well-separated resonances to many overlapping normal modes. [18] Which was given by:

$$f_c = 2000\sqrt{T/V}$$

where T is 60-dB reverberation time (T_{60}), V is the volume of the enclosure.

To select the optimal transition frequency in the current study, a novel optimized approach is employed to search the transition frequency. This transition frequency can be regarded as a combination point to combine the mentioned two methods.

Optimization Methodology

The objective of the current study is to optimize the efficiency and accuracy of the proposed combination methods so as to make transition frequency to be of their corresponding target values simultaneously. This is a multi-objective optimization problem since more than one parameter is to be optimized at the same time. Every slight change of the separation frequency leads to new values of computation time, memories, and RMS error. Therefore, a global search algorithm genetic algorithm is applied for searching the optimal separation frequency.

Genetic algorithm

The genetic algorithm is a metaheuristic inspired by the process of natural selection that belongs to the larger class of evolutionary algorithms. Genetic algorithm is commonly used to generate high-quality solutions to optimization and relying on biological inspired operators such as mutation, crossover, and collection. [23] Ou et al. employed a genetic algorithm combined with FEM and BEM for calculating the optimized natural frequency of plate structure. [24-26] In a genetic algorithm, four bio-inspired operators, including initialization, crossover, selection, and mutation, are the main procedure to search for optimized results. The initialization process generates the initial population randomly. The selection operator selects excellent individuals in the current generation for breeding the next generation of individuals. To avoid local convergence, the mutation operator changes one or more gene values in a chromosome for individuals in the next generation. In the whole process, the fitness quality is calculated by the fitness function. The fitness function is a key concept to evaluate the fitness of individuals in the search process.

Fitness Function

The genetic algorithm optimized the effects of computation time, memory, and RMS error to achieve the desired separation frequency. It is a multi-objective optimization problem since three factors can avoid the results simultaneously. The most straightforward multi-objective fitness function can be given as follows:

$$Minimize\ F = \sum \omega_n\, b_n$$

where ω_n is the weighting of the nth factors, which represents the importance of the nth objective. b_n is the nth objective factors which affect the selection of the optimization frequency. b_n is consists of computation time, CPU memory, and RMS error. Therefore, it is obvious that when F is minimized, the optimal results can be obtained. In this paper, the weighting schemes are based on the method of the coefficient of variation. The coefficient of variation (CV) is defined as follows:

$$C_{vn} = \frac{\sigma_n}{\mu_n}$$

Where σ_n denotes the standard derivation of the nth factors. μ_n denotes the mean value of the

nth factors. C_{vn} denotes the coefficient of variation of the nth factors. The weighting scheme is defined as follows:

$$\omega_n = \frac{C_{vn}}{\sum C_{vn}}$$

Optimization transition frequency approach

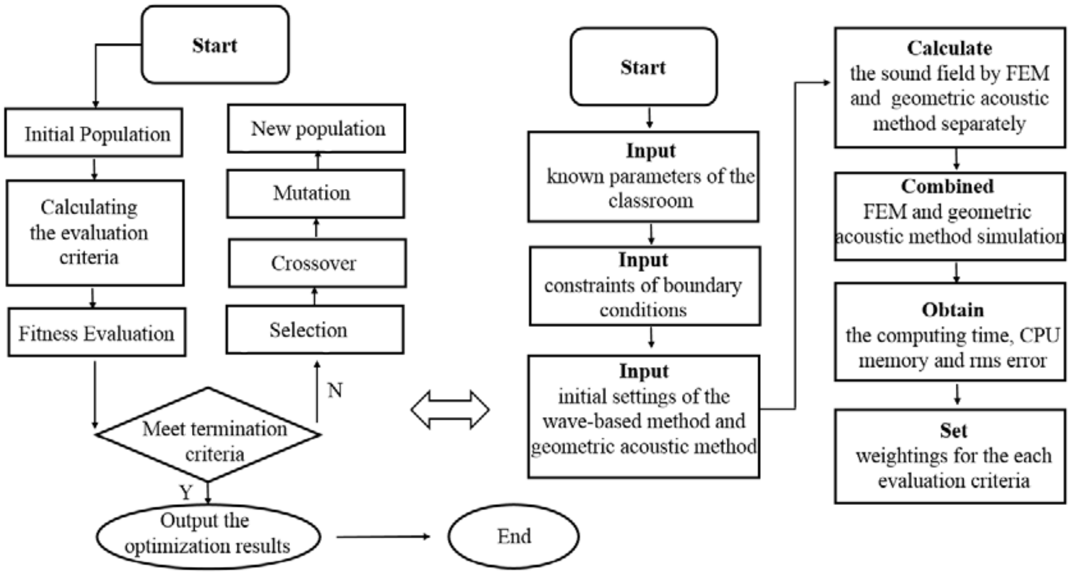

Fig. 1 Flowchart of the genetic algorithm procedure

The flowchart of the optimization frequency approach accompany with the combined FEM and geometric acoustics prediction methods is shown in Fig.1. It is shown that the genetic algorithm optimization model is given on the left side while the combination sound prediction methods are given on the right side. The whole optimal transition procedure is as follows: (1) input the known classroom characteristics, such as the classroom's length, width, height. (2) Input and boundary constraints, such as the boundary materials including the absorption coefficients scattering coefficients at different frequencies. (3) Input general settings for FEM and geometric acoustics methods in COMSOL servers. (4) Calculate the sound field by FEM and geometric acoustic separately under the concerned separation frequency. (5) Combined the proposed FEM and geometric acoustics methods results and obtain the computation cost factors (including computation time, CPU memory costs, and RMS value). (6) Set the termination criteria for the genetic algorithm. For instance, set the maximum tolerable error and maximum generations in the genetic algorithm. (7) Run the genetic optimization algorithm program to search the optimal frequency results.

Case studies and experimental validation

In this study, a package of genetic algorithm code was utilized for the optimization process, as shown in Fig.1. Based on the proposed methods, several case studies were conducted in real classrooms in the Hong Kong Polytechnic University (PolyU). The general characteristics of the selected classrooms were given in Table.1. In the genetic optimization algorithms, the initial population and max numbers of generation are 100 and 500, respectively. The crossover and mutation rates are 0.8 and 0.08, respectively. The computation costs were generated by the COMSOL FEM server. The general information for the FEM server was shown in Table. 2.

As for the experimental measurements, the room acoustical parameters were measured by using architecture acoustic software *DIRAC 6.0* (B&K Type 7841). The sound source used in the experiment was the Echo Speech source (B&K Type 4720). The signal collecting device was a pre-polarized free-field 1/2-inch microphone with B&K 2270 handheld sound level meter. Two sound sources and 4 positions of receivers were used in the current study. These sound source-receiver combinations were set according to ISO 3382-2. Yang and Mak reported the investigation of speech intelligibility and acoustical measurements by using *DIRAC*. *DIRAC* software was commercial software based on the measurement and analysis of room impulse response. [27-28] In the current study, the classroom impulse response was generated by an internal e-sweep source.

Case study 1

In this case, a small well-decorated (with acoustic treatments) rectangular classroom in PolyU was selected as the objective enclosure (see Fig. 2). The information of the classroom, materials of the classroom walls, general settings of the combined prediction methods are shown in Table.1. The absorption coefficients of the classroom boundaries at different frequencies were shown in Appendix A. In FEM method, boundary conditions were defined by the mix boundary conditions. The normal acoustic boundary impedances (Z_s) can be expressed by the sound absorption coefficient α:

$$Z_s = \rho_0 c \frac{1+\sqrt{1-\alpha}}{1-\sqrt{1-\alpha}}$$

Where ρ_0 is the density of the boundary materials. c denotes the sound velocity in the air. Free triangular meshes were selected for element discretization with the maximal size $h\_max =$ 0.18m. The amplifier of the Gaussian pulse was 4m^3/s. The calculated time period was from 0s to 3s within the time-step size $\Delta t = 0.7\ ms$.

A Gaussian impulse was used as the impulse response in the FEM methods. The characteristics of the Gaussian impulse was given in Table 2.

Fig.2 the schematic drawing of rooms in case 1(left) and photos of case 2(right).

Table 1 Classroom characteristic in the case 1

Length/m	Width/m	Height/m	Volume/m3	Number of seats
7.12m	7.88m	2.63m	147.558m3	40

Materials on each side of the classroom

Floor	**Side Walls**	**Ceiling**	**Windows**	**Door**	**Front and rear walls**
Loop pile tufted carpet	Painted concrete walls	Metal perforated plates	Double glazing windows	Solid wooden door	Wooden perforated plates

Table 2. General settings of wave-based methods and geometric acoustic methods

Finite Element Methods	h_max	N	Δt/total time	f_0	A	c_air
	0.12m	4	0.7ms/3s	f_c	4	343m/s
Geometric acoustic methods	Start frequency	Nrays	Δt/total time	Ray direction	Source power	c_air

			vector		
f_0	10000	0.1ms/3s	spherical	0.04W	343m/s

Where h_max is the maximal size of the mesh element. N is the number per wavelength required to resolve a harmonic wave with some accuracy. Δt is the size of the time-step. f_0 is the source frequency bandwidth, f_c is the upper cut-off frequency of f_0. A is the sound source amplitude.

The known parameters, boundary conditions, general settings, and optimal results are listed in the mentioned tables. The optimized approach procedure is the same as the one shown in Sec. 3. It can be seen from the tables that the optimal transition frequency can be found according to the restriction conditions obtained from the combination methods. In this study room, the wall was decorated with double glazing windows, as shown in Fig.2. The information of the classroom, general settings of the combined prediction methods is shown in Table. 1 and 2 respectively.

Case study 2

In this case, a small rectangular glass-decorated study room in PolyU was selected as the objective enclosure (see Fig.2). The information of the classroom, general settings of the combined prediction methods, and parameters in the genetic algorithms are shown in Table 3. The general settings of the combined prediction methods were the same as Case 1 in Table 2.

Table. 3 Classroom characteristics in case 2

Length/m	**Width/m**	**Height/m**	**Volume/m3**	**Number of seats**
7.84m	3.85m	2.68m	80.893m3	20

Materials on each side of the classroom					
Floor	**Side Walls**	**Ceiling**	**Windows**	**Door**	**Front and rear walls**
Loop pile tufted carpet	The double-glazing glass wall	Metal perforated plates	Double glazing windows	Solid wooden door	Painted concrete walls

Results

Optimization of the computation costs

A normal desktop manufactured in 2016, 8GB of memory, and Intel R Core (TM) i7-6800K processor (6 cores, 3.6GHz) was used for calculating the simulation cases. During the whole combined prediction model calculation process, the CPU and memory were less than 50% and 56%, respectively. The target of the optimization process was to minimize the computation costs to obtain the optimized separation frequency in the combined prediction methods.

The case studies introduced in Sec. 4 show the effective, optimized results of the proposed combination methods. For sound field prediction in a given classroom, the computation costs and accuracy are essential factors that affect to be considered. The proposed combination methods combined the wave-based methods and geometric acoustic methods. The proposed genetic algorithm optimization approach is used to search the balanced optimized results. By using the proposed methods, users can set the computation costs and accuracy error conditions according to the calculation results of the combination methods and identify the optimal results.

Table 4 Optimization results

		Case 1	Case 2
Schroder frequency		112Hz	131Hz
Optimized frequency		118Hz	133Hz
Weightings		$\omega_1 = 0.09, \omega_2 = 0.13, \omega_3 = 0.78$	$\omega_1 = 0.09, \omega_2 = 0.13, \omega_3 = 0.78$
Optimization	T_{total}	12993s	8228s
Results	M_{total}	19.82 GB	12.26GB
	RMS	2.03	2.88

In Table.4, "T_{total}" denotes the total simulation time (computation time of FEM and geometric acoustic methods) of the numerical approaches. "M_{total}" denotes the total memory costs (CPU memory costs of FEM and geometric acoustic methods) during the numerical computation process. "RMS" denotes the root-mean-squared error between the combined simulation results and measurements. "$\omega_1, \omega_2, \omega_3$" denotes the weightings of the computation time, memory cost, and RMS, respectively.

In these cases, the weightings of computation costs criteria are predefined by the coefficient of variation. Besides, the proposed methods can obtain optimal results, which depend on the weighting coefficients. The criteria for computation costs need to be normalized before an input in the optimization process.

Discussion

Effectiveness of computation cost at optimization frequency

In Table. 5, the effectiveness of the proposed combined optimization results was compared with the separated approaches. According to the equation stated in Sec.2, the Schroder frequency in Case 1 and Case 2 are 112Hz and 131Hz, respectively. The selected separation frequency is required to be higher than the Schroder frequency. In Table.5, the optimization process and results of several selected representative separation frequency in case study 1 are shown as follows.

Table.5 Comparison of computation cost among optimization frequency and selected frequency.

	Wave-based model		**GA model**		**Combination model**		
Freq.	T_{sim}	***Memory***	T_{sim}	***Memory***	T_{total}	M_{total}	***RMS***
Schroder	12708s	18.88GB	74s	784MB	12782s	19.65GB	2.82
125Hz	13445s	19.63GB	69s	702MB	13514s	20.34 GB	1.86
200Hz	13513s	20.51GB	68s	685MB	13581s	21.18 GB	1.58
250Hz	13714s	21.22GB	65s	680MB	13779s	21.88 GB	1.44
Optimized	12922s	19.11GB	71s	735MB	12993s	19.82 GB	2.03

In Table.5, "$Freq.$" denotes the separation frequency for the separated approaches. "T_{sim}" denotes the total simulation time of each numerical approach. "$Memory$" shows the memory cost during the computation process. "T_{total}" denotes the total simulation time (computation time of FEM and geometric acoustic methods) of the numerical approaches. "M_{total}" denotes the total memory costs (CPU memory costs of FEM and geometric acoustic methods) during the numerical computation process. "RMS" denotes the root-mean-squared error between the combined simulation results and measurements.

Comparison with other studies

A set of comparisons of the proposed regression curves with other studies were discussed in the following section. Previous studies on acoustic sound filed simulations of normal-sized classrooms were always based on the hybrid geometrical acoustic methods .[12-16] However, when it comes to small rooms, geometrical acoustic prediction methods appear to be flawed due to the inherent neglect of important low frequency wave effects, such as standing waves, diffraction, and interference. In order to assess the aural significance of using more accurate low-frequency modeling and applied in a real room, several combined wave-based and geometric studies were proposed in the previous study. [19-21] While in these studies, the authors proposed the combination methods focused on the combination of the results generated with both simulation techniques. They used a straightforward approach for combining both simulation results consist of low-pass/high-pass filtering the FE/ray-based results, both at the Schroeder frequency, and then simply adding the filtered frequency responses.

The combination methods in the mentioned studies were effective for combining wave-based and ray-based prediction modeling in a real room. While the computation costs seem not considered in the mentioned approaches. In this paper, the proposed genetic algorithm optimization method was used to search the optimal frequency, which was the transition frequency for separating the wave-based methods and geometric acoustic methods. The FEM methods were employed as wave-based methods for calculating the sound field in that frequency domain lower than the transition frequency. And geometric acoustic methods were employed in that frequency domain high than the transition frequency. Computation costs were the main criteria in the mentioned genetic algorithm optimization methods. Therefore, the main difference between the approaches in previous studies and the ones in this paper is the consideration of the computation costs.

Comparison of measurements and simulations

The Comparison between numerical predicted acoustical parameters and experimental acoustical parameters in Case study 1 were shown in Fig. 3-6. A summary of the results was given as follows:

For the results of reverberation time (RT) and early decay time (EDT): as expected, good agreement was found between the RT's in real and virtual classrooms. Compared to the measured values, the expected RT values were very similar, generally within 0.1 s, especially at low frequency (63Hz) within 0.15s. The EDT results were similar to RT, except that at low frequency (63Hz), prediction values up to 0.15s lower than measured results at lower frequencies.

The definition of C_{80} is shown as follows:

$$C_{80} = 10log\frac{\int_0^T h^2(t)dt}{\int_T^\infty h^2(t)dt}$$

Where "T" is time (80ms) elapsed after the arrival of the direct sound wave, and $h(t)$ is the impulse response.

For the results of Sound clarity (C80): the results are as expected, given that C80 is inversely related to RT and EDT, the results of the combined prediction model are generally within 1 dB different from the measurement, except at which it is up to nearly 2 dB lower at 8000 Hz. Prediction is up to 1dB higher than measurement at low frequency but within 2 dB higher than measurement at high frequency.

The definition of D_{50} is shown as follows:

$$D_{50} = 10log\frac{\int_0^{50ms} h^2(t)dt}{\int_0^\infty h^2(t)dt}$$

For the results of D50: the results are as expected, good agreement was found between the D50's in the real and virtual classrooms. The results of the combined prediction model are generally within 0.05 different from the measurement. Prediction is up to 0.05 lower than measurement at low frequency but within 0.05 higher than measurement at high frequency

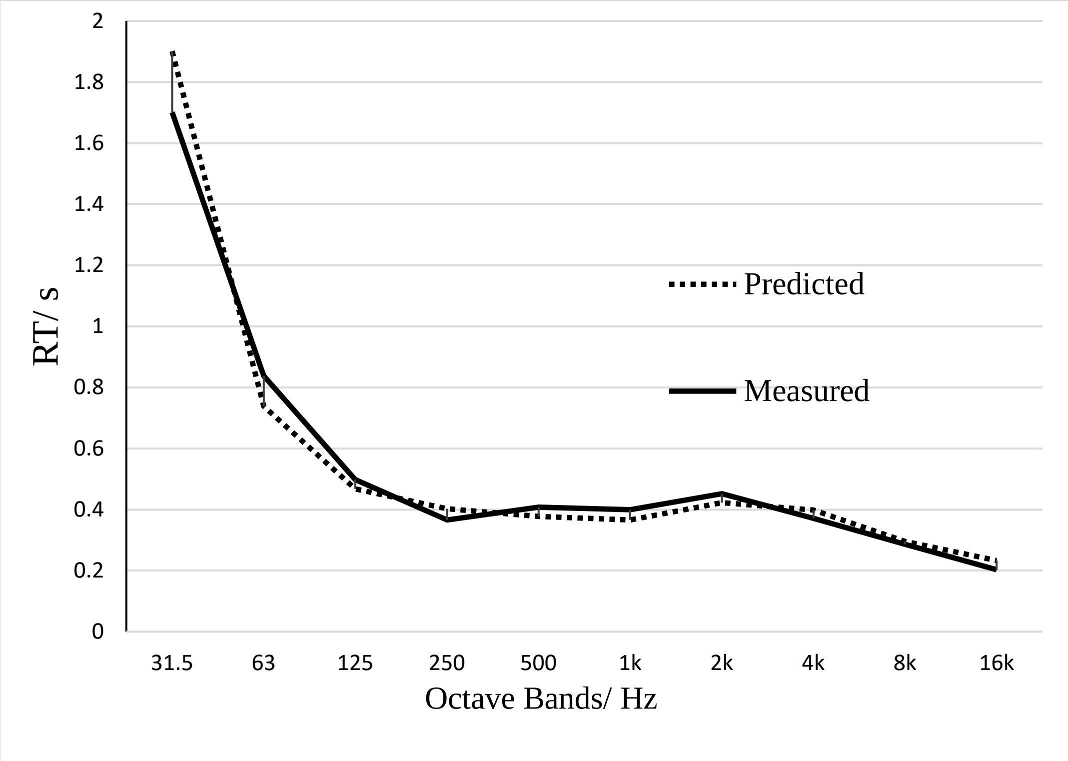

Fig.3 Comparison between predicted and measured results of RT

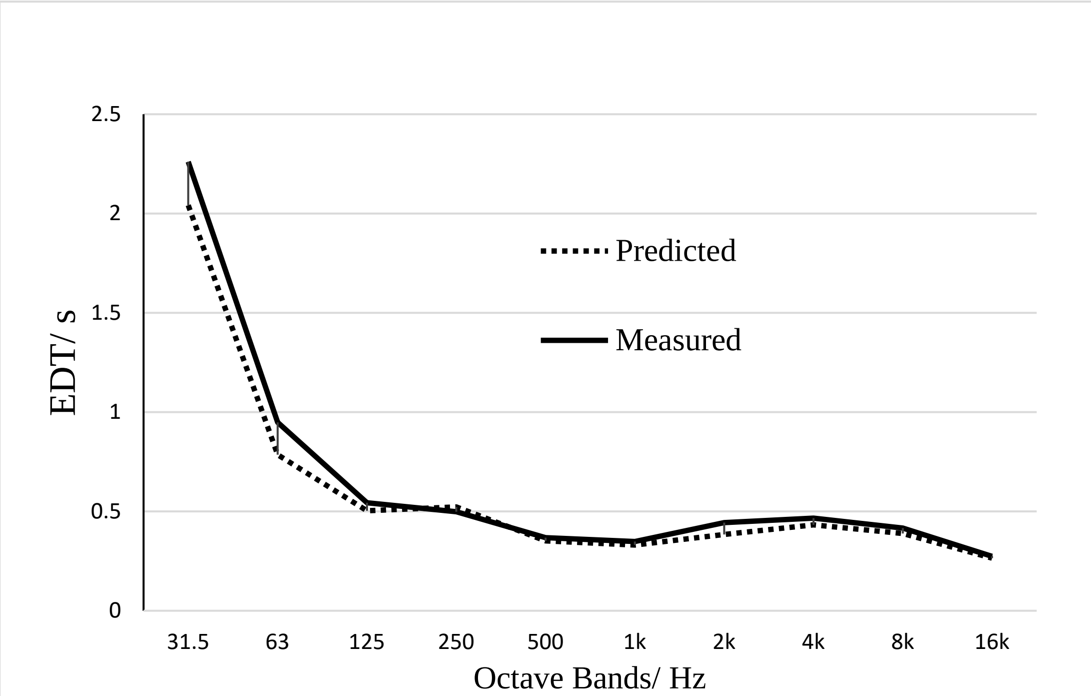

Fig.4 Comparison between predicted and measured results of EDT

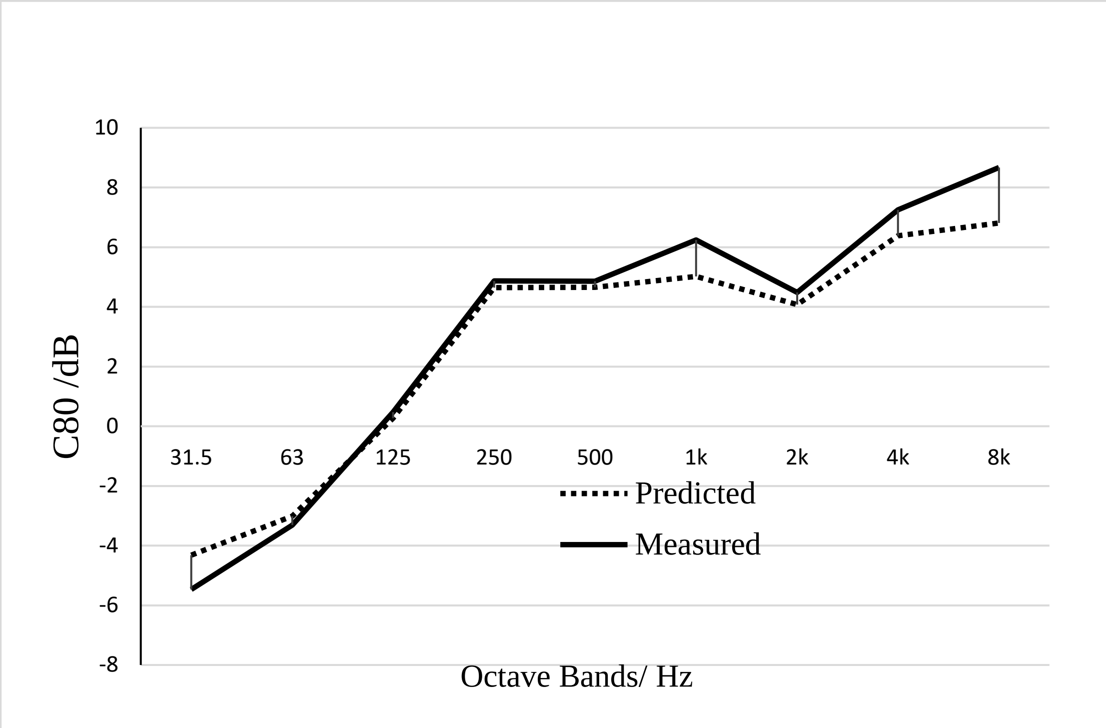

Fig.5 Comparison between predicted and measured results of C80

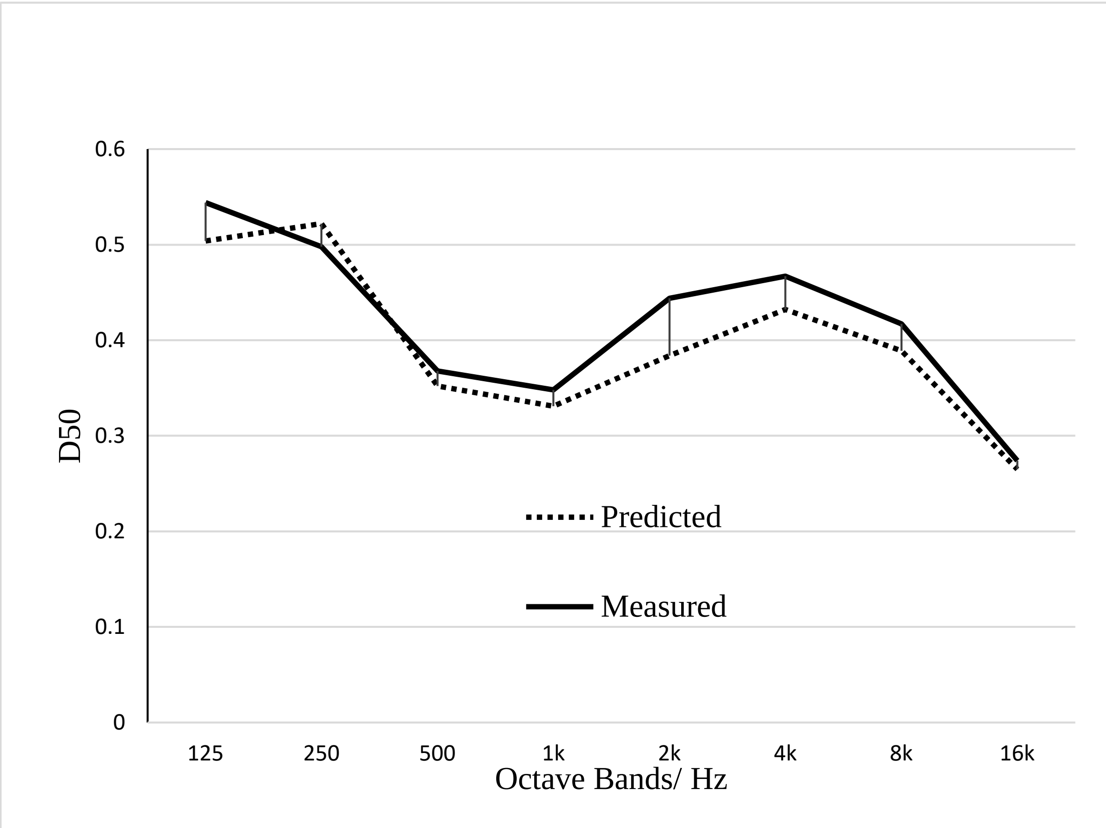

Fig.6 Comparison between predicted and measured results of D50

Limitations

In spite of the high relevance of simulated prediction data and experimental validation results, there still remain limitations for discussion. Some limitations in the simulation methods and classroom geometric models exist in the theoretical fundamentals. The following discussions are the factors influencing the simulation quality.

Limitations due to simulation methods

The finite element method is based on wave propagation equations that cover all relevant sound wave characteristics. Therefore, the simulation quality is mainly depended on the geometrical dimensions of the classroom model and boundary material sound coefficient data. However, the impedance boundary approach is limited by assuming the locally reacting boundary condition for a porous material. Dragonetti and Romano estimated errors in assuming the locally reacting boundary condition for porous materials. [29] The authors proved that the acoustic surface impedance depended on airflow resistivity, the type of wavefront impinging on its surface, the angle of wave incidence, and the thickness of the porous material.

In contrast to the FEM method, the ray tracing method (geometrical acoustics method) used many simplifications, assuming the sound propagation and sound reflection modes in the classroom. Possible problems in the reflection pattern of the impulse response can be attributed to the neglect of diffraction effects and the uncertainty of determining realistic low frequency scattering coefficients for boundary materials.

Limitations due to the classroom geometric model

As mentioned in the previous section, the classroom geometric model was built from detailed architectural structures and acoustically relevant features of the real classrooms. In this study, the classroom geometric model neglected some small objects and geometric details in the classroom. Even if we believed that these small objects and geometric details would not generally affect the simulation results, another limitation due to the classroom geometric model was several desks and chairs existing in the classroom. The reflection and diffraction effects at the positions of desks and chairs were possible reasons influencing the simulation quality. The limitations mentioned above are uncertainties in the classroom geometric model.

Conclusion

In the current paper, a combined wave-based and geometric acoustics prediction method is proposed in two small classrooms in university. A genetic algorithm is employed for searching the optimal transition frequency in view of the consideration of computation cost. FEM method is selected as the representative wave-based method applied at frequencies below the transition frequency. Hybrid geometric acoustic methods are applied at frequencies above the transition frequency. The proposed combination model offers the possibility to simulate the sound field in the whole audible frequency range in real small rooms. Several comparisons with other studies are discussed in the current study. Validation experiments are conducted in the same classroom. High correlation coefficient values between the combined prediction method and experimental measurements were proposed. The proposed combined prediction model was proved optimal methods for predicting the sound field in the classroom over the whole audio frequency domain in this study. The wave-based FEM part at low frequencies is useful and efficient for predicting the low-frequency sound fields. In practice, applications of the proposed combined prediction model can provide the predicting sound fields in buildings that are essential to acoustical designs and acoustic environmental assessments.

Acknowledgments

The author(s) disclose receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by a PhD studentship funded by the Hong Kong Polytechnic University.

Author Contribution Statement:

Da Yang: Conceptualization, Methodology, Simulation, Formal analysis, Investigation, Experiment, Writing **-** Original Draft.

Cheuk Ming Mak: Conceptualization, Methodology, Investigation, Resources, Writing **-** Review & Editing, Supervision.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] M. Kleiner, B.I. Dalenback, P. Svensson, "Auralization—an overview," J. Audio Eng. Soc. 41(11) (1993) 861-875.

[2] L. Savioja, P. Svensson, "Overview of geometrical room acoustic modeling techniques," J. Acoust. Soc. Am. 138(2) (2015) 708-730.

[3] C.M. Mak, Z. Wang, "Recent advances in building acoustics: An overview of prediction methods and their applications," Build. Environ. 91(2015) 118-126.

[4] C.M. Mak, C. Ye, J. Wu and J. Yang, "Prediction of flow-generated noise produced by an in-duct spoiler in a ventilation system using CIBSE Guide B5 method", Build. Serv. Eng. Res. Technol. 30(2) (2009) 153-167.

[5] C.M. Mak, W.M. To, T.Y. Tai and Y. Yun, "Sustainable noise control system design of building ventilation systems, " Indoor Built Environ. 24(1) (2015) 128-137.

[6] C.Z. Cai, C.M. Mak, "Noise control zone for a periodic ducted Helmholtz Resonators system," J. Acoust. Soc. Am. 140 (6) (2016), EL471-EL477.

[7] C.Z. Cai, C.M. Mak, and X.F. Shi, "An extended neck versus a spiral neck of the Helmholtz resonator," Appl. Acoust.115 (2017), 74-80.

[8] E. Premat, Y. Gabillet, "A new boundary-element method for predicting outdoor sound propagation and application to the case of a sound barrier in the presence of downward refraction," J. Acoust. Soc. Am. 108(6) (2000) 2775-2783.

[9] C.M. Mak, Y.P. Lui, "The effect of sound on office productivity," Build. Serv. Eng. Res. Technol. 33(3) (2012) 339-345.

[10] K. Kowalczyk, M. van Walstijn "Room acoustics simulation using 3-D compact explicit FDTD

schemes," IEEE Trans. Audio. Speech. Lang. Process. 19 (2010) 34-46.

[11] L. Savioja, "Real-time 3D finite-difference time-domain simulation of mid-frequency room acoustics," in Proceedings of the 13th International Conference on Digital Audio Effects, (DAFx-10), Graz, Austria (2010).

[12] J.Y. Jeon, H.S Jiang, H.I. Jo, "Acoustic evaluation of orchestra occupancies in concert halls: Effect of sound absorption by orchestra members on audience acoustics," Build. Environ. 145 (2018) 349-357.

[13] A. Astolfi, V Corrado, A Griginis, "Comparison between measured and calculated parameters for the acoustical characterization of small classrooms," Appl. Acoust. 69 (2008), 966-976

[14] P. Zhu, F. Mo, J. Kang, G. Zhu, Comparisons between simulated and in-situ measured speech intelligibility based on (binaural) room impulse responses, Appl. Acoust. 97 (2015) 65-77.

[15] W. Yang, M. Hodgson, "Validation of the auralization technique: Comparative speech-intelligibility tests in real and virtual classrooms," Acta Acust. 93 (2007) 991-999.

[16] M. Hodgson, N. York, W. Yang, M. Bliss, "Comparison of predicted, measured and auralized sound fields with respect to speech intelligibility in classrooms using CATT-Acoustic and ODEON," Acta Acust. 94 (2008) 883-890.

[17] M. Kavraz, "The acoustic characteristics of the Çarşı Mosque in Trabzon, Turkey, " Indoor Built Environ. 25(1) (2016) 128-136.

[18] M. R. Schroeder, K. H. Kuttruff, "On Frequency Response Curves in Rooms. Comparison of Experimental, Theoretical, and Monte Carlo Results for the Average Frequency Spacing between Maxima," J. Acoust. Soc. Am. 34 (1962) 76-80.

[19] Y. Wang, S. Safavi-Naeini, S. Chaudhuri, "A hybrid technique based on combining ray tracing

and FDTD methods for site-specific modeling of indoor radio wave propagation," IEEE T. Antenn. Propag. 48 (2000) 743-754.

[20] J. Summers, K. Takahashi, Y. Shimizu, T. Yamakawa, "Assessing the accuracy of auralizations computed using a hybrid geometrical acoustics and wave-acoustics method," J. Acoust. Soc. Am. 115 (5) (2004) 2514- 2515.

[21] M. Aretz, "Combined wave and ray based room acoustic simulations of small rooms," Ph.D. thesis, RWTH Aachen, Germany, 2012

[22] COMSOL Multiphysics, "Reference Manual," COMSOL AB, Sweden, 2014

[23] Mitchell, Melanie (1996). An Introduction to Genetic Algorithms. Cambridge, MA: MIT Press.

[24] D. Ou, C.M. Mak, "Optimization of natural frequencies of a plate structure by modifying boundary conditions," J. Acoust. Soc. Am. 142 (2017) EL56-62.

[25] D. Ou, C.M. Mak, "Modification of boundary condition for the optimization of natural frequencies of plate structures with fluid loading," Adv. Mech. Eng. 10 (8) (2018) 1-11.

[26] D. Ou, "An Optimization Method for Maximizing the Low Frequency Sound Insulation of Plate Structures," Shock. Vib. 2018 (2018) 1-8.

[27] D. Yang, C.M. Mak, "An investigation of speech intelligibility for second language students in classrooms," Appl. Acoust. 134 (2018) 54–59.

[28] D. Yang, C.M. Mak, “Effects of acoustical descriptors on speech intelligibility in Hong Kong classrooms," Appl. Acoust. 171 (2021) 107678.

[29] R. Dragonetti, R.A. Romano, "Errors when assuming locally reacting boundary condition in the estimation of the surface acoustic impedance," Appl. Acoust. 115 (2017) 121-130.

Appendix A

Sound absorption coefficients of materials for the classroom's boundary at different frequencies.

Boundary Materials	125Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz	16k Hz
Loop pile tufted carpet	0.1	0.4	0.62	0.7	0.63	0.88	0.75	0.75
Wooden perforated plates	0.1	0.45	0.75	0.6	0.7	0.7	0.28	0.16
Metal perforated plates	0.59	0.8	0.82	0.65	0.27	0.23	0.1	0.1
Painted concrete walls	0.02	0.03	0.03	0.03	0.04	0.07	0.07	0.1
Double glazing windows	0.1	0.07	0.05	0.03	0.02	0.02	0.02	0.02
Solid wooden door	0.14	0.1	0.06	0.08	0.1	0.1	0.1	0.1

Seats with students sitting on	0.24	0.4	0.78	0.98	0.96	0.87	0.87	0.6

Figures and Tables

Figure 1

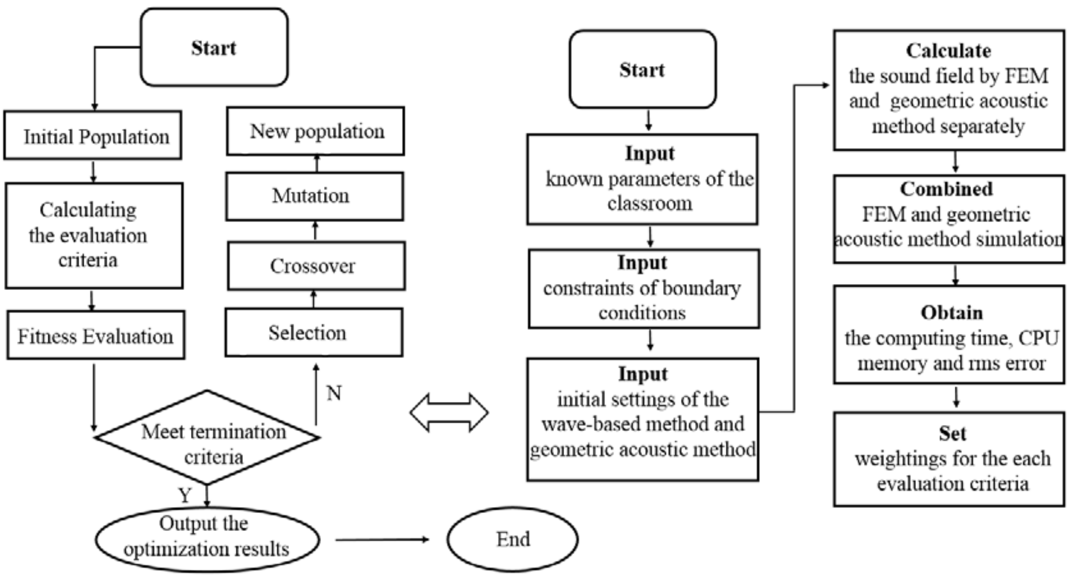

Fig. 1 Flowchart of the genetic algorithm procedure

Figure 2

Fig.2 the schematic drawing of rooms in case 1(left) and photos of case 2(right).

Figure 3

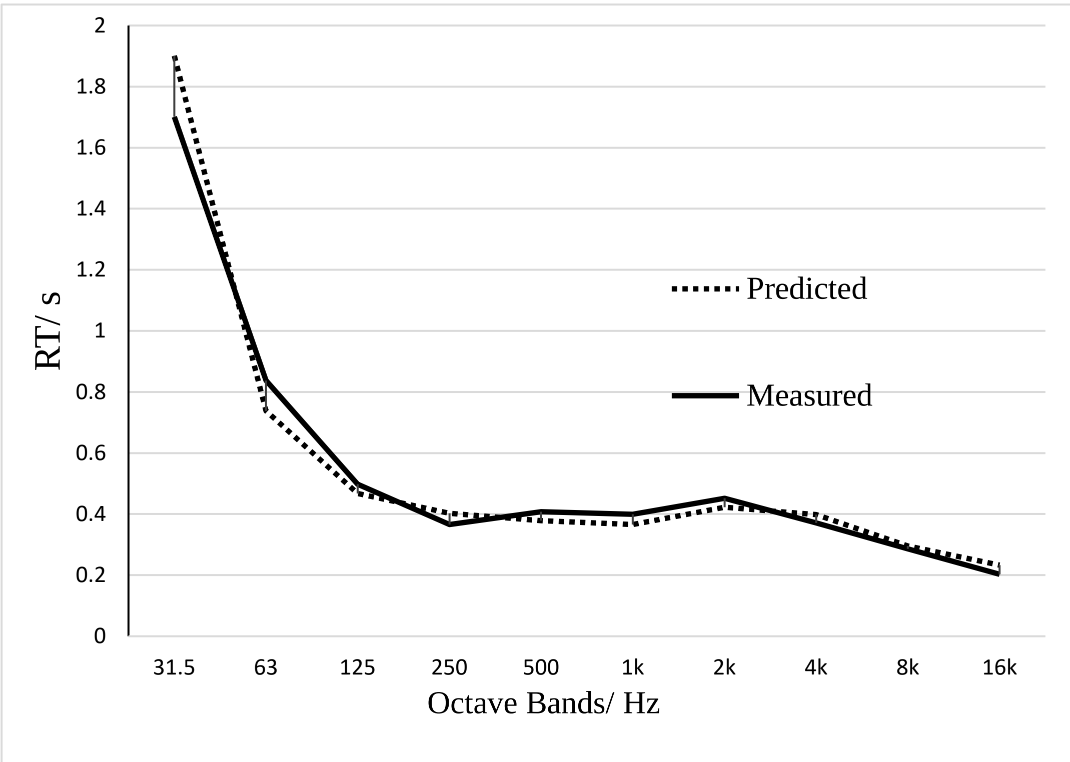

Fig.3 Comparison between predicted and measured results of RT

Figure 4

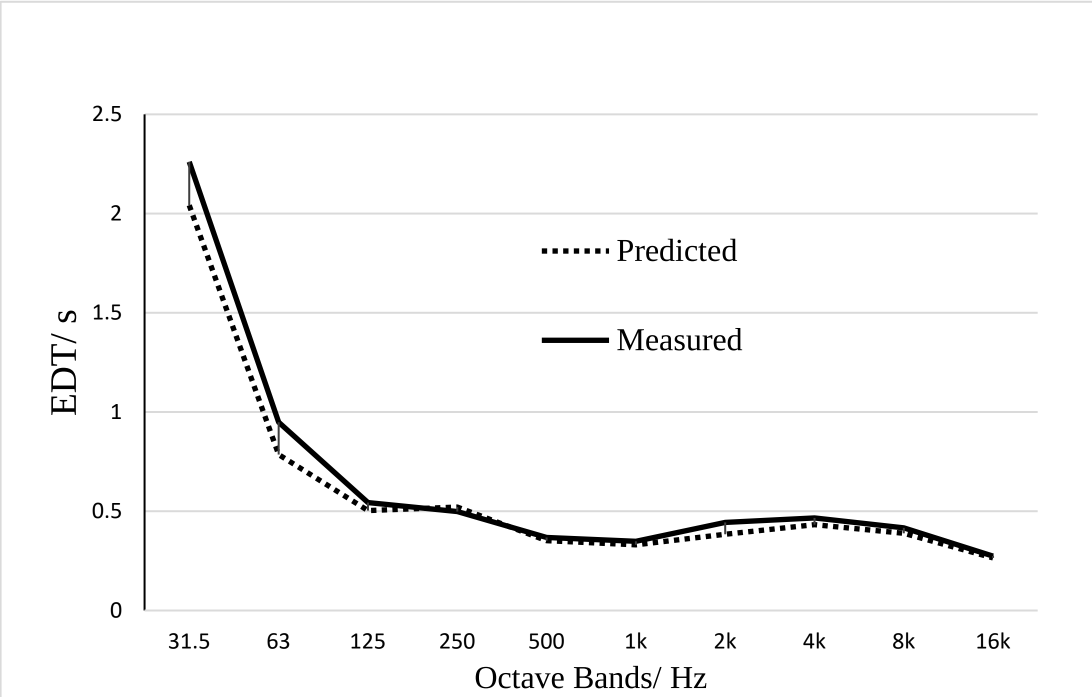

Fig.4 Comparison between predicted and measured results of EDT

Figure 5

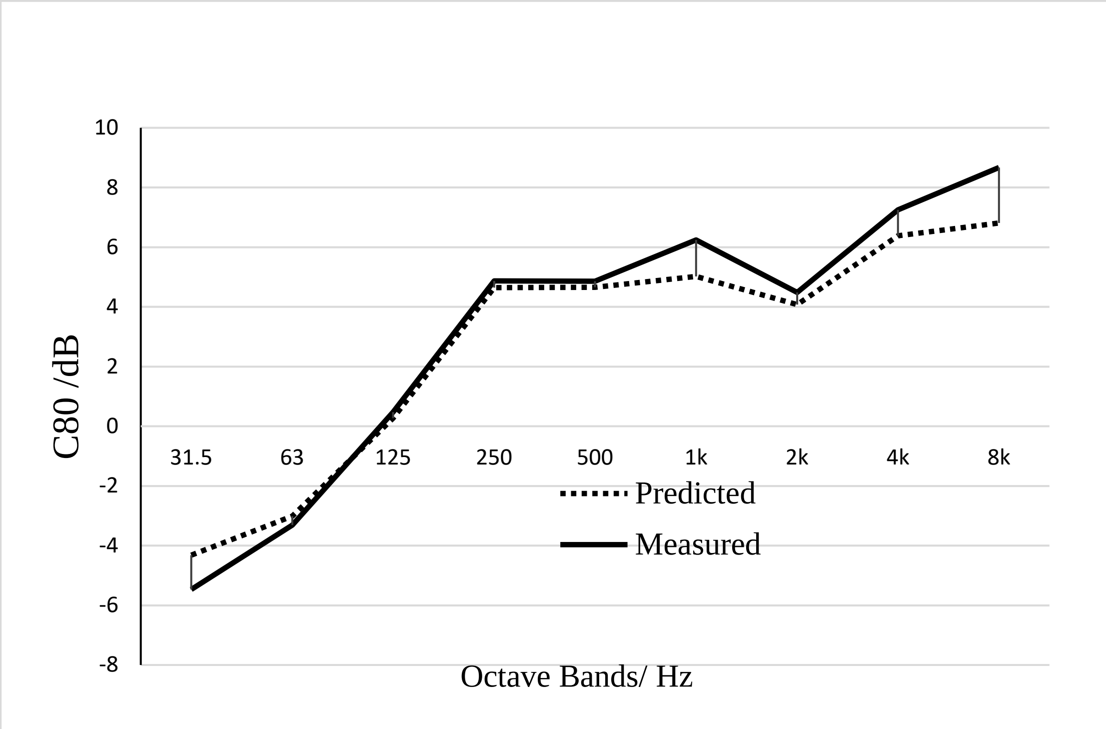

Fig.5 Comparison between predicted and measured results of C80

Figure 6

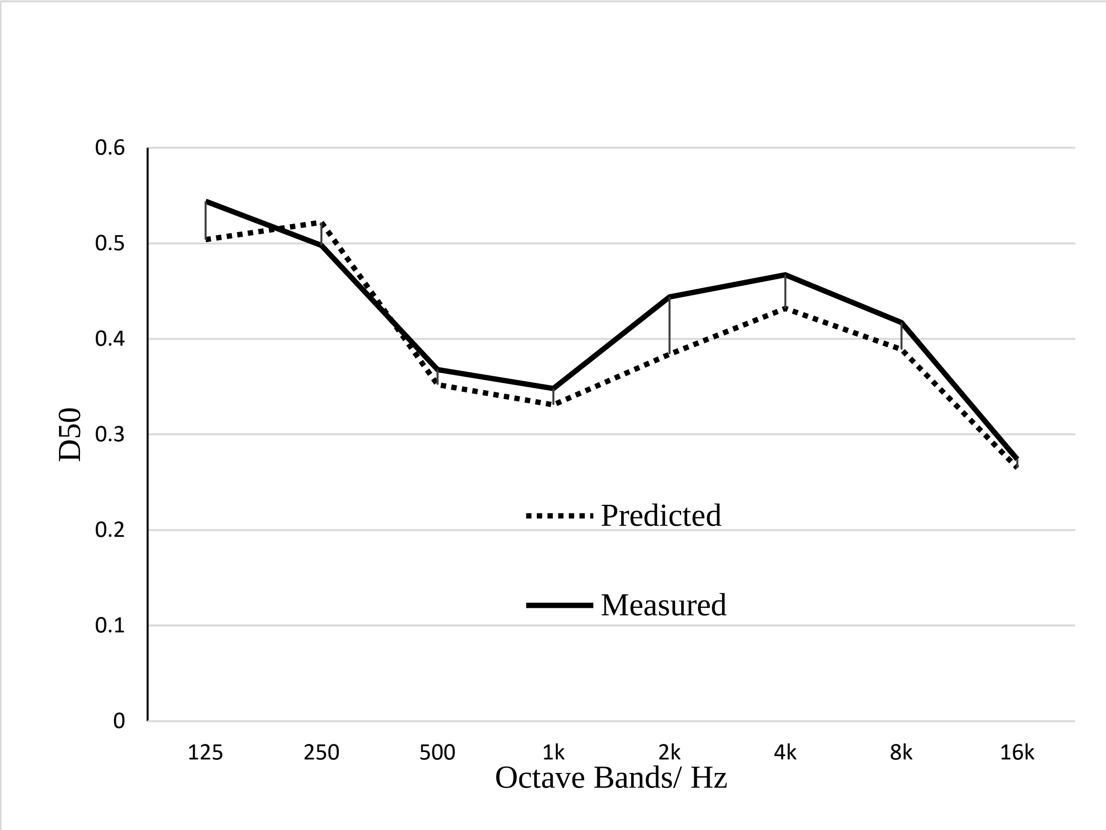

Fig.6 Comparison between predicted and measured results of D50

Table 1

Table 1 Classroom characteristic in the case 1

Length/m	Width/m	Height/m	Volume/m3	Number of seats	
7.12m	7.88m	2.63m	147.558m3	40	
Materials on each side of the classroom					
Floor	**Side Walls**	**Ceiling**	**Windows**	**Door**	**Front and rear walls**
Loop pile tufted carpet	Painted concrete walls	Metal perforated plates	Double glazing windows	Solid wooden door	Wooden perforated plates

Table 2

Table 2. General settings of wave-based methods and geometric acoustic methods

Finite Element Methods	h_max	N	Δt/total time	f_0	A	c_air
	0.12m	4	0.7ms/3s	f_c	4	343m/s
Geometric acoustic methods	Start frequency	Nrays	Δt/total time	Ray direction vector	Source power	c_air
	f_0	10000	0.1ms/3s	spherical	0.04W	343m/s

Table 3

Table. 3 Classroom characteristics in case 2

Length/m	**Width/m**	**Height/m**	**Volume/m3**	**Number of seats**	
7.84m	3.85m	2.68m	80.893m3	20	
		Materials on each side of the classroom			
Floor	**Side Walls**	**Ceiling**	**Windows**	**Door**	**Front and rear walls**
Loop pile tufted carpet	The double-glazing glass wall	Metal perforated plates	Double glazing windows	Solid wooden door	Painted concrete walls

Table 4

Table 4 Optimization results

		Case 1	Case 2
Schroder frequency		112Hz	131Hz
Optimized frequency		118Hz	133Hz
Weightings		$\omega_1 = 0.09, \omega_2 = 0.13, \omega_3 = 0.78$	$\omega_1 = 0.09, \omega_2 = 0.13, \omega_3 = 0.78$
Optimization Results	T_{total}	12993s	8228s
	M_{total}	19.82 GB	12.26GB
	RMS	2.03	2.88

Table 5

Table.5 Comparison of computation cost among optimization frequency and selected frequency.

	Wave-based model		**GA model**		**Combination model**		
Freq.	T_{sim}	***Memory***	T_{sim}	***Memory***	T_{total}	M_{total}	***RMS***
Schroder	12708s	18.88GB	74s	784MB	12782s	19.65GB	2.82
125Hz	13445s	19.63GB	69s	702MB	13514s	20.34 GB	1.86
200Hz	13513s	20.51GB	68s	685MB	13581s	21.18 GB	1.58
250Hz	13714s	21.22GB	65s	680MB	13779s	21.88 GB	1.44
Optimized	12922s	19.11GB	71s	735MB	12993s	19.82 GB	2.03