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Scaled-model measurements for coupled volumes using an automated high spatial-resolution scanning system

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ABSTRACT

This paper presents an experimental study of low frequency behavior in coupled volumes. In order to examine low frequency behavior in coupled volumes, an eighth-scale model of two coupled volumes with an automated high spatial-resolution scanning system has been developed. The validation of the system on spatial resolution and reverberation times are examined before measurements. The validated scanning system makes it possible to acquire thousands of room impulse responses on a designated planar grid with a fine grid size in the scaled model. The high spatial-resolution scanning results are used to investigate the characteristics of acoustic wave propagation in both single-space and coupled-volume systems. Temporal behaviors of sound pressure propagations in the scaled model will be demonstrated with integrated measurements in both rooms. The results will show diffraction through aperture opening and reflection phenomena in the system. Scanning results with an acoustic particle velocity sensor will visualize sound energy flows between coupled-volume systems. The directions and magnitudes of sound energy flows are represented with two dimensional vector arrows. The presented scanning results are highly dependent on variable coupling aperture sizes and frequencies. This paper also discusses some design issues relevant to high quality, high spatial resolution scanning, to diffusely reflecting interior surfaces.

INTRODUCTION

Recently, architectural acousticians have been increasingly interested in concert halls that employ coupled volume geometry as a design resource. The coupled-volume system consists of two or more rooms which are connected by opening apertures. The system can be characterized by non-exponential sound decays. In a closed room, the sound decays exponentially if diffuse sound fields can be assumed. In case of the coupled volume, the sound energy decays breaks the exponential rule because of sound energy exchange between rooms. If the secondary room that is attached to the primary room has longer reverberation time than the primary room, the late sound energy is fed back from the secondary room to the primary room. This sound energy exchange between volumes causes non-single-slope decays. This phenomenon has significance in the potential for attaining both of counter-active room parameters; reverberance and clarity. Because of its promising potential, many researchers are focused on the investigation of coupled volume systems to identify the mechanism of the system. Various methodologies have been used in the research. The statistical acoustics (SA) model was investigated by Cremer et al [1**]** and Kuttruff **[**2**]**. Energy density functions are derived from ordinary differential equations that are based on power balance in each room. SA models can explain non-exponential sound energy decay curves without heavy computational loads. The decay curve is dependent on the ratio of room volumes, surface area, absorption coefficients, and aperture size. In recent studies, numerical methods, i.e. boundary element method, finite element method [3] and time-domain finite difference method [4], have been used to simulate the wave behavior in coupled spaces. Validation of numerical simulations has become a great concern for many researchers. Acoustic scale modelling [5] can be a substantial alternative even though relatively little research has been executed within this area. This paper, discusses investigations on wave phenomena in a coupled-volume system using an eighth scale model of a coupled volume system. The automated scanning system with a high spatial resolution is developed to measure impulse responses accurately to examine the sound fields of the system.

LITERATURE REVIEW

De la Cruz [5] developed an automatic scanning system to study the spectral behavior of a scaled coupled volume. He acquired a large number of impulse responses in predefined grids. The energy based analysis showed modal behavior in the sound fields and gave hints of energy exchange between rooms. Ermann [6] measured IRs at each seat in a 400 seat hall. He compared the measurement results with 1:20 scale-model and computer modeling results. The mapping of the measurements revealed the spatial variations of acoustic parameters especially in low frequencies. He found that the scale modeling showed better predictions of spatial variation than computer modeling. Xiang and Blauert [7] developed tenth-scale binaural scale modeling. Head related sound receiver measurements and digital processing procedure for a binaural auralization technique were presented. Jing and Xiang [8] developed the diffusion equation model to visualize steady-state sound pressure distribution and time-dependent energy flow in coupled volumes. The simulations found the dip of the energy-flow decay and demonstrated the energy feedback from the secondary room via the animations. The characteristics are dependent on the size and location of the aperture.

SYSTEM OVERVIEW

The eighth scale model for coupled-volume and automated scanning system is implemented to investigate the sound field. The measurement system in this paper scans sound fields in the coupled-volume scaled-models automatically by a mechanical scanning system. The automated scanning system is implemented to locate outside of the scaled-model to remove intervention on measurments' results. Two stepper motors are mounted on the top of the model to control the microphone position to Cartesian x-axis and y-axis respectively. A 5 mm diameter of omni-directional microphone is used as a receiver. Two custom made speakers are used as sound sources to excite the room. Scaled mini dodecahedron speaker is aimed for high frequencies excitation and the other loudspeaker is for low frequencies excitation covering frequency range between 300 Hz and 45 kHz. The position of the speakers is subject to change depending on the measurement tasks.

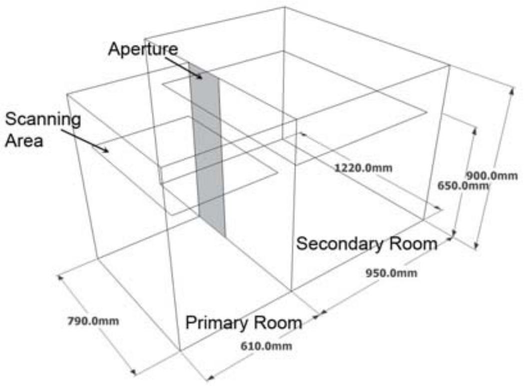


Figure 1 Dimensions of the scaled model.

Figure 1 presents the sketch and physical dimensions of the scaled model. The volume of primary room is 0.0433 m^3 (222 m^3 for the real scale) and secondary room is 1.0431 m^3 (534m^3). The microphone scans a plane which is 65 cm above the floor of the model. The maximum scanning area is approximately 73 percentage of model's floor area. The interior surfaces of the room are covered with custom-made 6" by 6" diffuser panels. It is designed by introducing random numbers over two dimensions of the surfaces to enhance the diffuseness in the room.

SYSTEM VALIDATION

The system needs to be validated before measurements and data analysis for further investigations. The spatial resolution must be guaranteed to acquire high frequency sound field measurements. Nyquist spatial theorem suggests the upper limit frequency when the microphone spacing distance is given. When the spacing is 1 cm which is the highest spatial distance in the current investigation, the theoretic upper limit frequency is 1,715 Hz in real-size. However, the practical upper limit frequency is lower than the theoretic limit frequency because misalignment errors may occur during scanning. The spatial resolution was validated by double-checking before and after measurements physically and analytically. Visualizaton of measurements results show that the maximum frequency in the system is 1.5 kHz (in real-size).

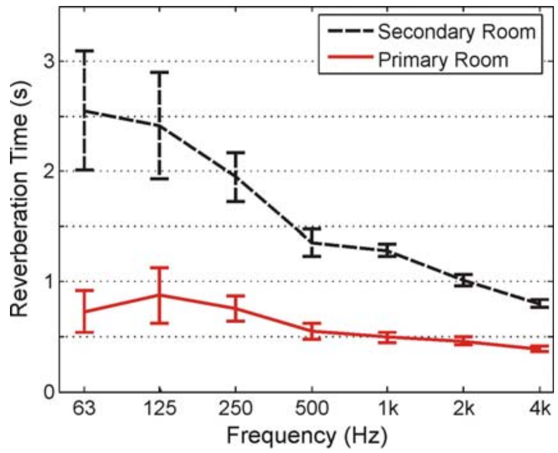


Figure 2 Spatially averaged reverberation times (T30) of the each rooms.

Natural reverberation times (T30) in both rooms are calculated from the measurement when the rooms are decoupled. To optimize energy exchange between the room, sound absorptive material is added in the primary room to make differences of decay times between rooms greater. Absorptive material is distributed evenly in the primary room to keep the sound fields diffuse. **Figure 2** presents spatially averaged T30 values from the measurement. Bars in the figure indicate standard deviations from the average values. In 1 kHz octave band, the reverberation time of the main room is approximately 0.5 seconds for the primary room and 1.28 seconds for the secondary room. In low frequency octave band, the deviation is larger than high frequencies because of modal behaviors. The standard deviation becomes smaller as the frequency increases and the sound field can be regarded as diffusive over 500Hz octave band.

EXPERIEMENT RESULTS & ANALYSIS

Experiment setup

Figure 2 illustrates the scanning areas of the measurements. The scanning areas are 30cm by 52 cm on both side of aperture. The sound sources are located at left bottom of the main room. A sampling frequency of 100 kHz is used. A log sine-sweep signal is used to excite the room. Two sessions which were measured separately in the primary room and secondary room are integrated to study sound propagation in the system.

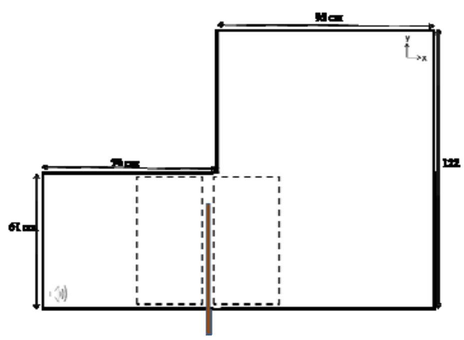
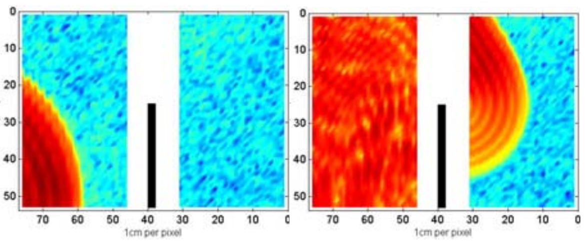


Figure 3 Scanning area of the measurement.

Temporal behaviors of sound pressure propagations

Figure 4 is the snapshots of animations of sound pressure propagation at 1 kHz in the time domain. The animation illustrates how the sound travels from the primary room to the secondary room. **Figure 4.(a)** shows the sound wave propagates towards the aperture. **Figure 4.(b)** shows when the sound enters into the secondary room. **Figure 4.(c)** shows diffraction and interference phenomena through the opening. It also shows reflections from the walls are overlapped with direct sound. **Figure 4.(d)** shows main room's energy decay faster than secondary room because of differences in size and absorption. Also the figure shows high energy 'dots' are concentrated in front of aperture and energy coming back from the secondary room. It is not obvious as much as direct sound's propagation but certain amount of energy comes back to the primary room.

(a) T=2ms (b) T=10ms



(c) T=12ms (d) T=192ms

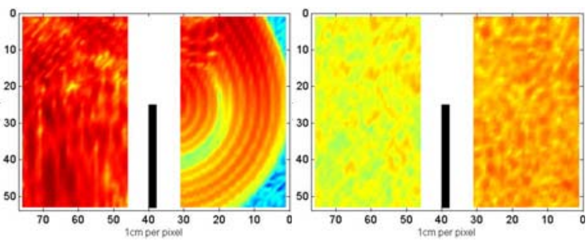
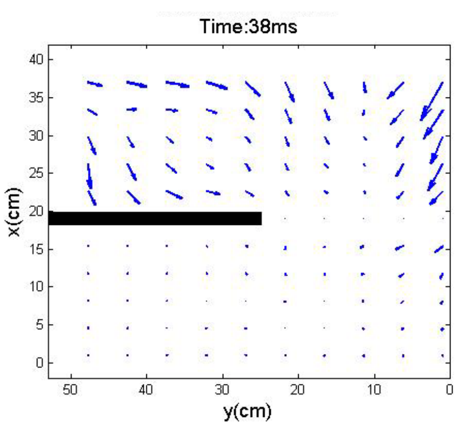


Figure 4 Snapshots of animation of the squared pressure over time in the 1 kHz octave band frequency.

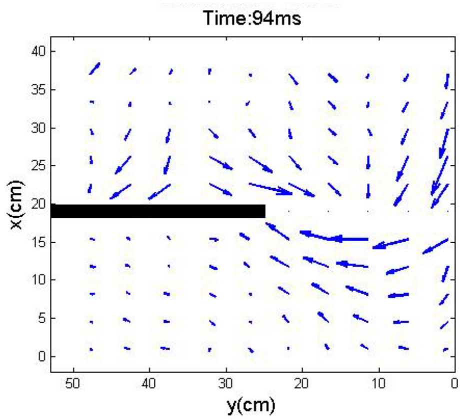
Sound intensity measurement

Sound intensity is the time average of the instantaneous product of the pressure and particle velocity impulse responses. Intensity measurement with Microflown p-u probe was conducted near the aperture in the primary and secondary room with the same scanning areas.

(a)



(b)



(c)

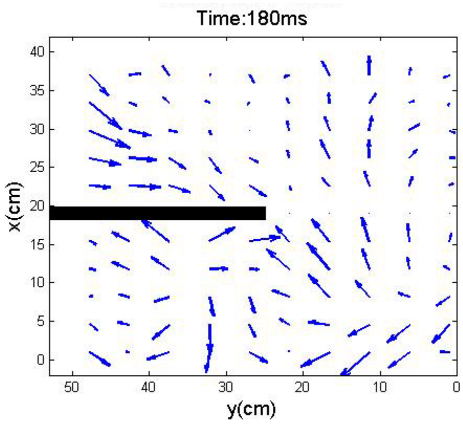


Figure 5 Snapshots of animation of intensity measurement at 125 Hz. Top part is in the primary room, the bottom part is in the secondary room.

Figure 5 presents snapshots of intensity animations in the 125Hz. The intensity was averaged for 5ms. The results demonstrate that directions of intensities are gradually changed from toward secondary room to toward primary room in the animation. It implies the tendency of direct sound travel to the secondary room and, after that, the energy coming back from the secondary room to the primary room. The results behave in accordance with the visulization results of the diffusion equation's model. [8]

DISCUSSION AND CONCLUSIONS

An eighth-scaled model of coupled volume has been implemented and used for acoustic measurements with a high spatial resolution scanning. Room impulse responses are acquired with an automated mechanical system according to predefined Cartesian grid areas. The validation of the system on a spatial resolution and reverberation times were examined before measurements. Temporal behavior of sound fields in a coupled-volume system is examined with integrated measurements in both rooms. Temporal pressure distribution demonstrates diffractions through the aperture opening and reflection phenomena in the system. Lastly, energy intensity analysis with an acoustic particle velocity sensor visualizes sound energy flows between coupled-volume systems.

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