Generalized alternative image theory to estimating sound field for complex shapes of indoor spaces

Byunghak KONG[1]; Kyuho LEE[2]; Seokjong JANG[3]; Seo-Ryong PARK[4]; Soogab LEE[5]

[1–5] Seoul National University, Republic of Korea

ABSTRACT

An alternative image theory that can efficiently simulate sound propagation inside a closed space, especially multiple reflections, is proposed. This method defines image spaces according to configuration of a real space, and image receivers instead of image sources are allocated with respect to their local coordinates. As compared to the original image theory, the alternative theory is more effective to develop propagation paths involved with reflections regardless of condition variables such as the number of reflections and combinations of reflecting surfaces. The positions of image receivers located in an image space corresponds to where sound waves that experiences the specific number of reflections related to the order of the image spaces reach to real receivers. Therefore, the sound field inside the real space is obtained by inverting the entire image spaces into the real space, which implies superposition. Basically, it is applicable to convex spaces, e.g. a rectangular hexahedron. Also, concave spaces and spaces that have partitioned into sub-spaces can be covered by the alternative theory.

Keywords: Alternative Image Theory, Image Space, Indoor Propagation   I-INCE Classification of Subjects Number(s): 25.4

1. INTRODUCTION

As the human body was exposed to strong blast waves generated inside a closed space, potential damages such as hearing loss and rupture of eardrum are a great concern because acoustic energy remains within the space instead of diverging into the atmosphere. Practically, shock waves reflected from enclosing surfaces can return to the body, and consequently, B-duration also becomes longer than outdoors. According to waveform parameter-based damage risk criteria (DRCs), e.g., MIL-STD-1474D by U.S. Department of Defense (1), that is one of the most commonly used type of DRCs, as peak sound pressure level (SPL) and B-duration increase, the rating level assessed by blast wave also increases.

Typically, experimental approaches on damage risk assessment for indoor spaces are not acceptable because various environmental parameters such as dimensions of a space, operating conditions, and measurement locations can affect the indoor sound field, so it is appropriate to estimate the field using numerical approaches. Kong et al. (2) developed an efficient method, so-called "alternative" image theory than can simulate multiple reflections of shock fronts using image space concept, and estimated the sound field from indoor muzzle blast instead of numerical schemes such as dispersion-relation-preserving (DRP) by C. Tam (3). Although they accurately obtained the locations of major shock fronts, the shape of the space were restricted to rectangles because parts of image spaces can be overlapped during expanding procedures.

In the present study, we proposed a guideline to configure higher-order image spaces without overlapping problem. In Section 2, image space concept were introduced and briefly reviewed. In addition, validity concept was introduced and implemented on expansion of three different type of image space, i.e., convex polygons, concave polygons, and sectioned spaces. In Section 3, numerical

[1] bhgong03@snu.ac.kr
[2] bukha16@snu.ac.kr
[3] clickcoco@snu.ac.kr
[4] tjfyd11@snu.ac.kr
[5] solee@snu.ac.kr

examples were shown and discussed about accuracy and reliability of the updated model. Finally, concluding remarks including future works followed in Section 4.

2. METHODOLOGIES

2.1 Image Space Concept – Overlapping Problem

The image space is an extension of the image receiver concept. It is opposite to the image source and can be considered as a set of image receivers. Therefore, the image space is determined by inverting the real space or lower-order image space, symmetrical with respect to their boundaries, like a procedure obtaining the location of an image receiver as described in Fig. 1-(b). The most remarkable advantage of image space concept is that it can be defined and configured regardless of reflecting paths. Furthermore, because they individually correspond to specific conditions of reflection such as the number of reflections and combination of reflecting boundaries, superposition of each reflected sound field can be simply obtained by inverting higher-order image spaces into next-lower-order image spaces or the real space.

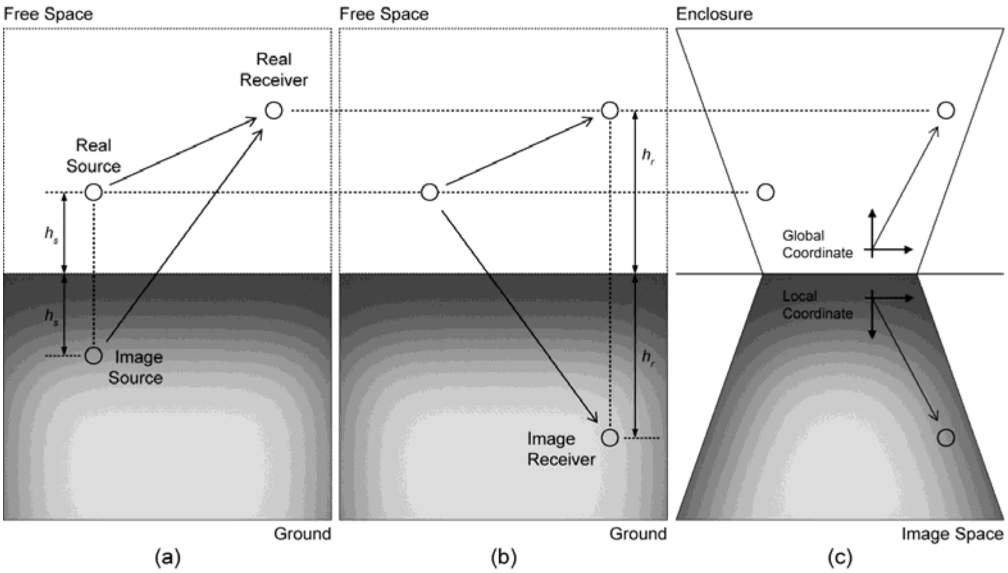

Figure 1 – Comparison of three concepts for (a) image source, (b) image receiver, and (c) image space

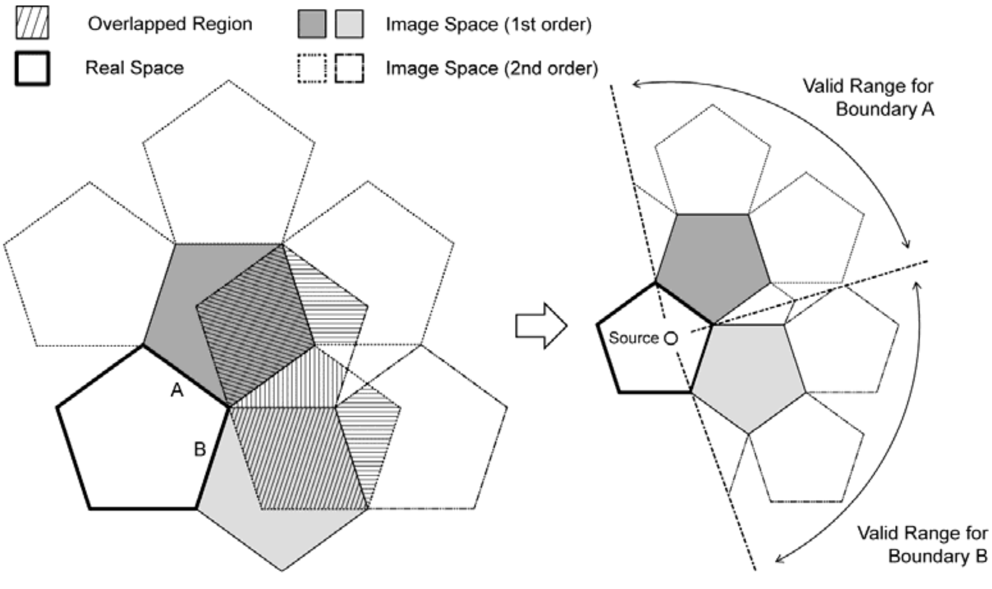

Figure 2 – Description of overlapping problem for two-dimensional pentagons

However, if the real space is not a rectangle as like previous study, part of image space can be overlapped as shown in Fig. 2. In this case, because sound field predicted in overlapped area might be superimposed twice, the total sound field inside the real space is overestimated. In this research, overlapping problem can be resolved by validity concept for imaginary boundaries and receivers.

2.2 Image Space Configuration – Validity

By definition, exterior of real space indicates entire reflected sound field, and a specific point or region corresponds to a specific reflecting condition. In order to specify the potential region for a specific condition, exterior region was divided into several sub-regions. They were called as valid ranges for each boundary and mean reflected sound fields by them as shown in Fig. 3-(a) regardless of the number of reflections and reflecting paths. The part of image space inside the valid range indicates the potential area for reflections by the corresponding boundary. In the same manner, validity of grid points and receivers can be defined. They were valid only if they were located inside the valid range, or it is invalid as indicated as blank diamond in Fig. 3-(d).

It is more complex to define validity of boundaries. Basically, it is valid if, at least, one of the end points of boundary is inside the valid range as shown in Fig. 3-(b). Exceptionally, although there is no valid grid point on the second order image space, only one boundary is conditionally valid because part of it is included inside the valid range like Fig. 3-(d).

When the higher-order image spaces were configured, the valid range is divided into a couple of sub-ranges depending on the next-lower-order reference boundaries. However, in some cases, when a part of sub-region is out of range, it should be abandoned as described in Fig. 3-(c).

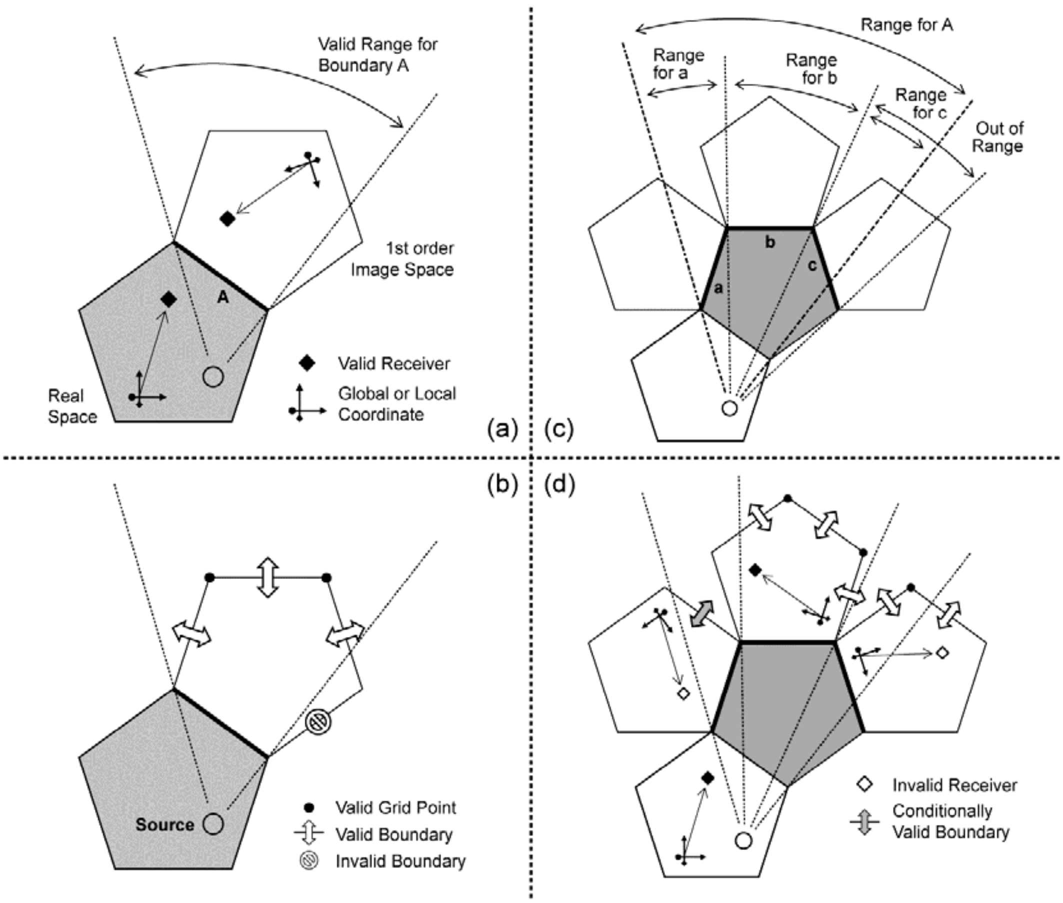

Figure 3 – Description of valid receiver, grid point, and boundary

2.3 Subspaces

When a space consists of complex boundaries, it can be resolved by dividing into several subspaces like Fig. 4-(a). In this case, the space was divided into six regions, and subspace including real source was assigned to be primary. Then, trans-boundaries that comprise the subspaces but are not reflecting boundaries can be defined. They were indicated as dotted lines in Fig. 4-(a). After that, similar steps are preceded from the primary subspace. The only difference of trans-boundary is that it construct another image space has a different shape with the reference cell as shown in Fig. 4-(b).

The overlapping problem can be resolved by valid ranges for the boundaries of the primary cell as shown in Fig. 4-(c) and 4-(d).

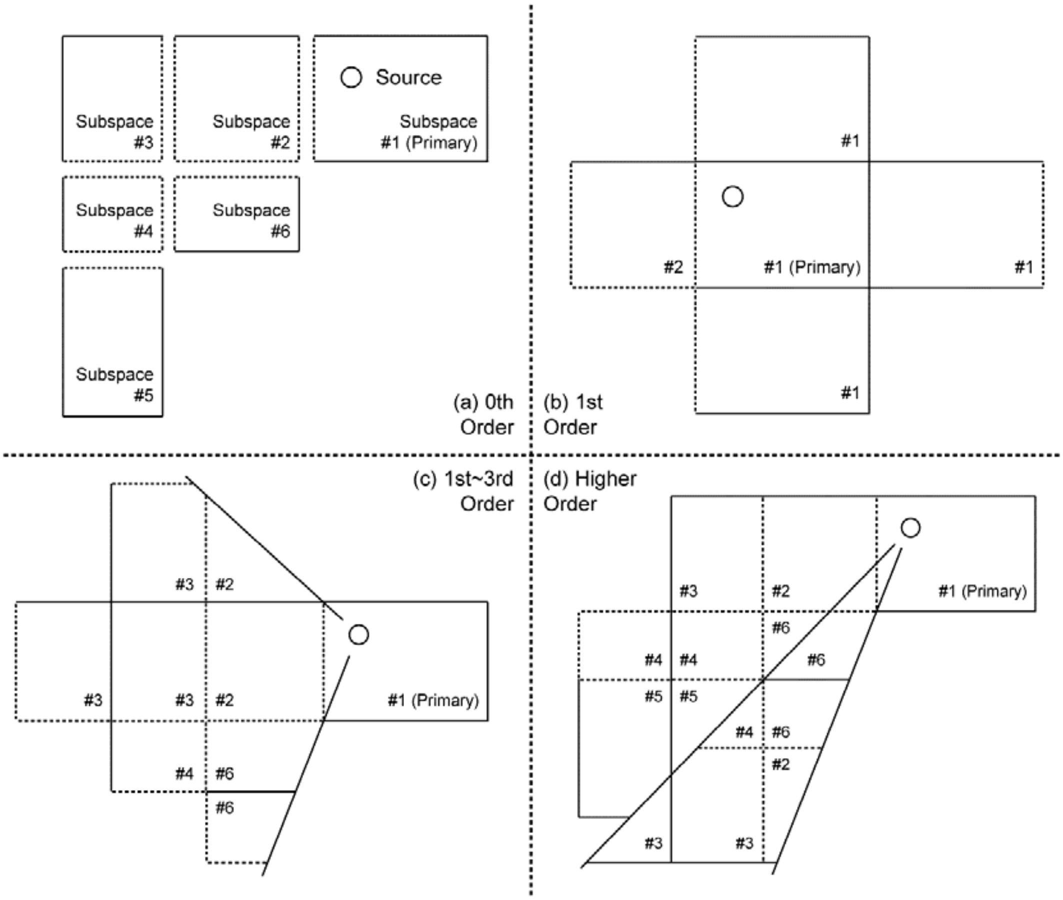

Figure 4 – Description of subspace and configuration of high-order image spaces

3. NUMERICAL RESULTS

3.1 Validation

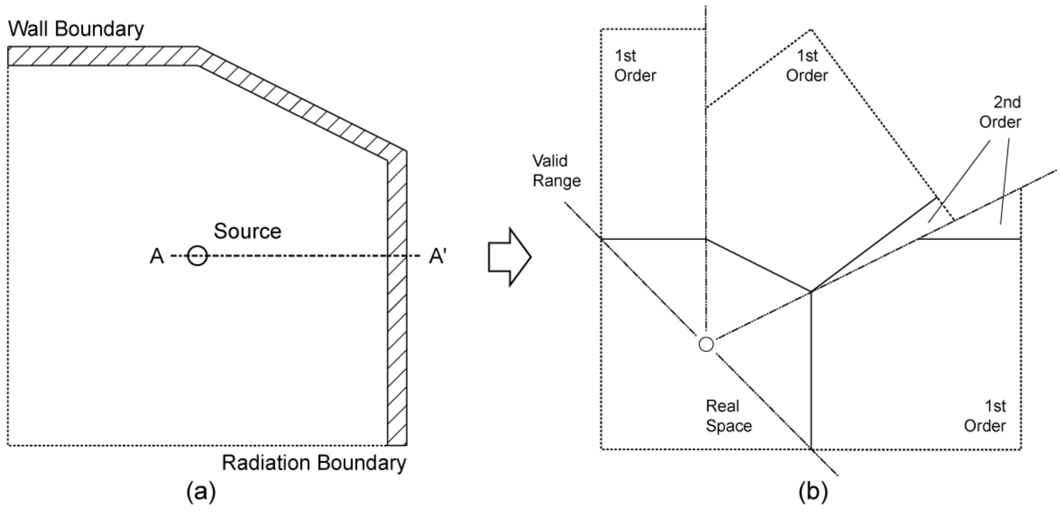

Figure 5 – Image space configuration of two-dimensional convex space

The reliability of the alternative image theory on irregular geometry was verified by comparison with the predicted results by the DRP scheme. The two-dimensional real space that were enclosed by three wall boundaries at the upper and right side and two radiation boundaries at the lower and left side were considered. As a result, image spaces can be obtained like Fig. 5-(b). Three primary valid ranges can be defined, and consequently, three first order image spaces were configured. However, they were partially excluded because they were out of ranges. Furthermore, radiation boundaries restricted the image spaces up to the third order cell. Therefore, the number of image receivers can be limited.

In order to simulate the impulse response on the computational domain for the alternative image theory, the exact solution that is a function of time and space were introduced as follows (1):

$$p(x, y, t) = \rho = \frac{\varepsilon_1}{2\alpha_1} \int e^{-\xi^2/4\alpha_1} \cos(\xi t) J_0(\xi\eta) \xi d\xi \tag{1}$$

where ε_1=0.01 and α_1=(ln2)/9. The three wall boundaries were treated as perfectly reflecting walls, which mean their reflection coefficients were assumed to be unity. The temporal variation of pressure distribution on a horizontal line, A-A', was shown in Fig. 6.

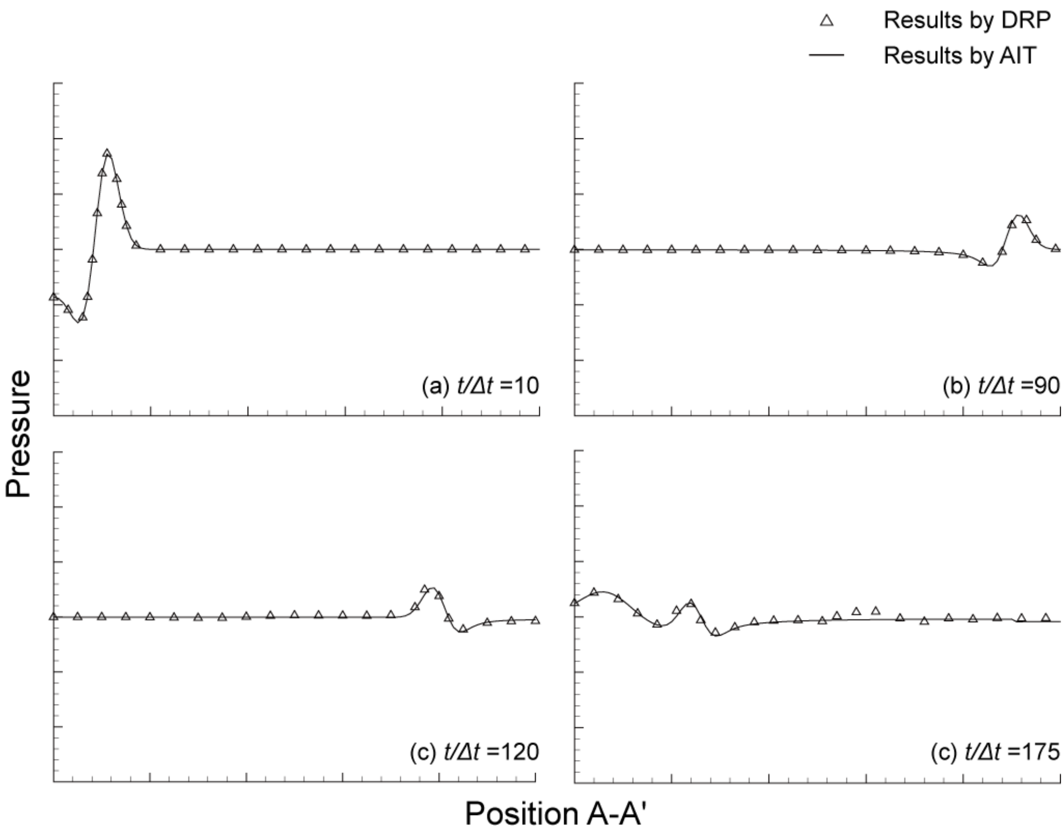

Figure 6 – Comparison of the numerical results by the alternative image theory and DRP

As shown in this figure, the predicted results by the alternative image theory, which are described as solid lines, agreed well with those by DRP scheme, which are shown as triangles. This means that the alternative image theory can simulate the multiple reflections inside a closed space in an effective way.

3.2 Indoor Analysis in Complex Geometry

Finally, the propagation of blast wave inside a space which has a complex shape was simulated by the alternative image theory and discrete wavefront method (2). Figure 7 shows a test space and the estimated results of peak SPL distribution at a specific height inside the space. As shown in this figure, peak SPL was effectively predicted for complex geometry.

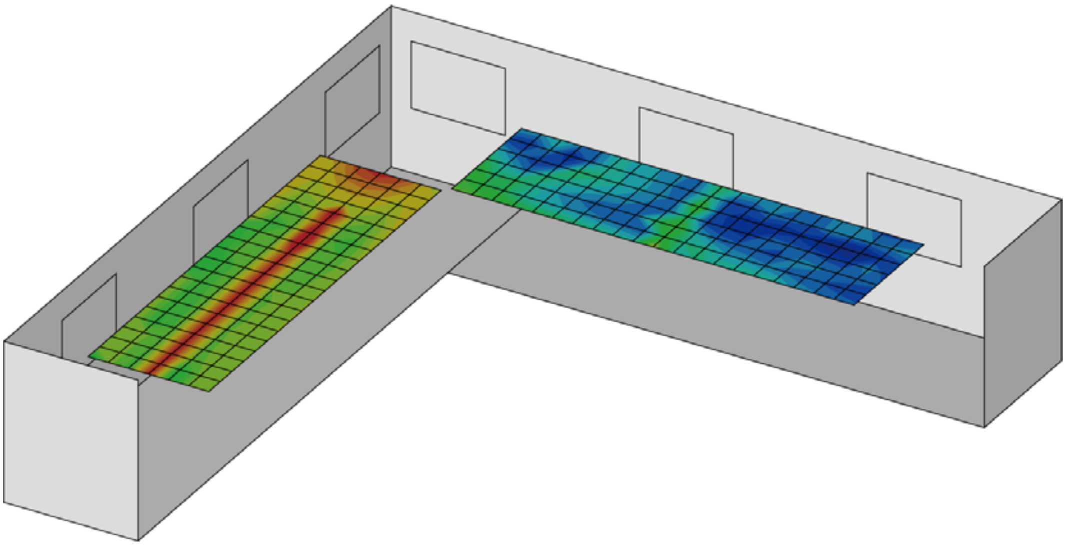

Figure 7 – Image space configuration and peak SPL distribution over the space

4. CONCLUSIONS

In the present study, validity concept for imaginary boundaries and receivers were introduced to resolve the overlapping problems. As a result, the receivers in the exterior region correspond to proper image space and the same reflected sound field did not be superimposed more than twice. Furthermore, when the space is a concave type or separated by some partitions, image spaces can be configured by dividing the real space into a sufficient number of convex polygons.

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