EVALUATING STAGE SOUND FIELD
FOR ACOUSTIC DESIGN BASED ON BOUNDARY ELEMENT METHOD

PACS REFERENCE: 43.55.Ka

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ABSTRACT

The purpose of this paper is to establish a way to evaluate stage sound fields in acoustic design at low frequencies based on the boundary element method (BEM). We calculate the sound field in a stage enclosure using BEM and evaluate the effect of the stage shell configuration in improving the transfer function at low frequencies. Measurements were also taken at an actual hall stage after it was constructed. The validity of modeling is examined through the measured and calculated results. The influence of on-stage orchestra performers and reflectors above the stage is also discussed based on simulated and measured results.

INTRODUCTION

Three methods are used to predict and evaluate sound fields in acoustical designs: -- (1) analysis based on geometrical acoustics, (2) experiments using acoustic scale models, and (3) analysis based on wave acoustics. Methods (2) and (3) are used to take into account the physical wave nature of sound, which is not negligible at low frequencies. When this is used in actual acoustic designs, wave acoustic analysis has the advantages of requiring less time and cost in constructing or modifying models.

We applied wave acoustic analysis to acoustical designs of auditoriums, calculating sound fields in stage enclosures with the model limited to the stage area. Comparing calculated and measured results, we discuss the validity of modeling. Future studies in evaluating stage sound fields should take into account the influence of orchestra performers, and we propose ways of considering this influence in wave acoustic analysis.

CALCULATING SOUND FIELDS IN STAGE ENCLOSURES

1. Theory of calculation. The integral equation method [1] is used to calculate a sound field. The velocity potential at observation point P is expressed in equation (1) (fig.1). When point P converges to p on surface S, equation (2) becomes.

$$j(P) = j_D(P) + \frac{1}{4p}\iint_S \left([j]\frac{\partial}{\partial n}\left(\frac{1}{r}\right) - \left[\frac{\partial j}{\partial t}\right]\frac{1}{cr}\frac{\partial r}{\partial n} - \left[\frac{\partial j}{\partial n}\right]\frac{1}{r} \right) dS \qquad (1)$$

$$\frac{1}{2}j(p) = j_D(p) + \frac{1}{4p}\iint_S \left([j]\frac{\partial}{\partial n}\left(\frac{1}{r}\right) - \left[\frac{\partial j}{\partial t}\right]\frac{1}{cr}\frac{\partial r}{\partial n} - \left[\frac{\partial j}{\partial n}\right]\frac{1}{r} \right) dS \qquad (2)$$

where j…velocity potential, r…distance between point P (or p) and a point on S, c…the sound speed, j D…direct component and brackets represent retarded values.

The velocity potential distribution on the boundary surface is obtained by solving equation (2) assuming a boundary condition on surface S, yielding the velocity potential at point P in volume W from equation (1) by substituting solutions from equation (2).

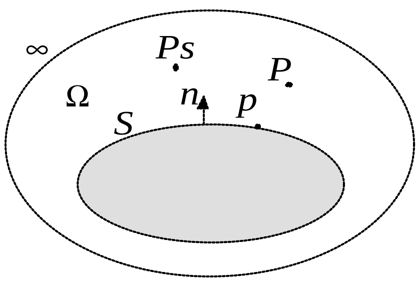

Fig. 1. Representation of the integral equation method

Table 1 Method and condition of calculation

Method	Integral equation method with BEM Using SYSNOISE[2] application software
Modeling	Treated as an exterior problem
Boundary	$dj/dn = 0$ (rigid)
Element	Maximum length 45 cm Elements 10409, Nodes 10405 (type A)
Source	Frequency 125 Hz Triangle 4 ms
Time step	1 ms (calculate to 140 steps)

2. Models evaluated. Two types of models are used in the calculation using the above method. The one for model shapes is shown in figure 2. Receive points and source points are shown in figure 4. Type A (fig.2) has a diffused surface and type B a flat surface. Because the proscenia of the models are treated as openings, the models are dealt as exterior problems. Representative

calculated results are shown in figure 5, which provides a frequency response analyzed from a time response directly obtained by transient analysis. The result of S11-P11 suggests that

(i) from 100 Hz to 250 Hz, the level difference between the peak and dip of the frequency response of type A is smaller than that of type B.

(ii) at 60 Hz, the frequency dip of type A is narrower and deeper than that of type B.

We thus conclude that type A is acoustically advantageous over type B in flat transmission characteristics at low frequencies. The result of S1-P1 suggests that, in the flatness of frequency characteristics, type A is advantageous over type B.

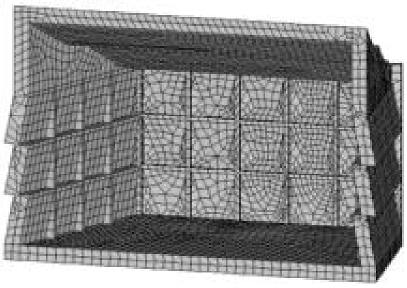

Fig. 2. Model shape (type A) type B has a flat surface

Fig. 3. Hall stage that was measured

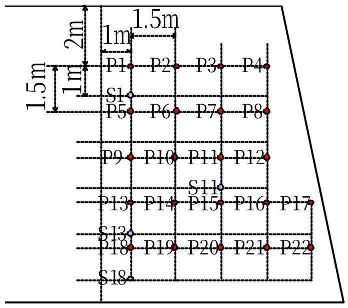

Fig. 4. Points for evaluation
(Receive points height at 1.2 m; source points height at 1.5 m)

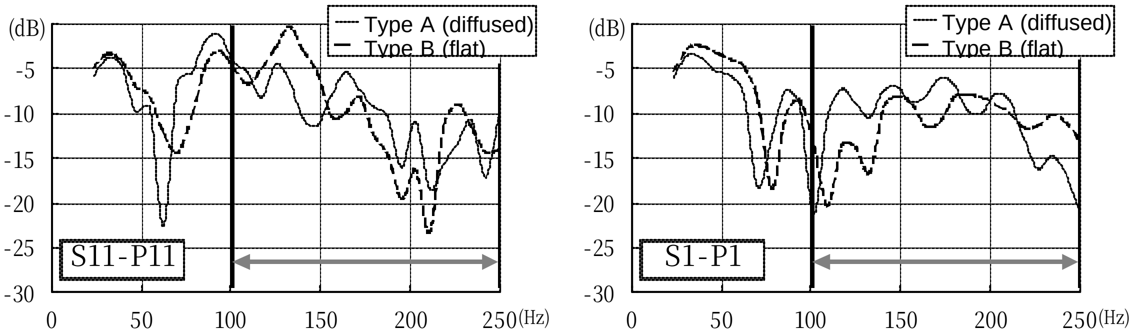

Fig. 5. Calculated results
(S11-P11 means that the source point is set at S11 and the receive point at P11)

COMPARING MEASURED AND CALCULATED RESULTS

The shape of the model used for comparison is shown in figure 2. Measurements are done in an actual hall stage (fig. 3). The model has the same size and shape as the actual hall but is limited to the stage area. The measured impulse response is convolved with a triangular wave for comparison with the calculated response.

Figure 6 shows a comparison of the calculated and measured results. The calculated response in the time domain agrees closely with the measured response. At the frequency domain, which is calculated from the time domain response, the results roughly agree, verifying the validity of this modeling, i.e., using a model that is limited to the stage area, treating it as an exterior problem, and calculating with BEM.

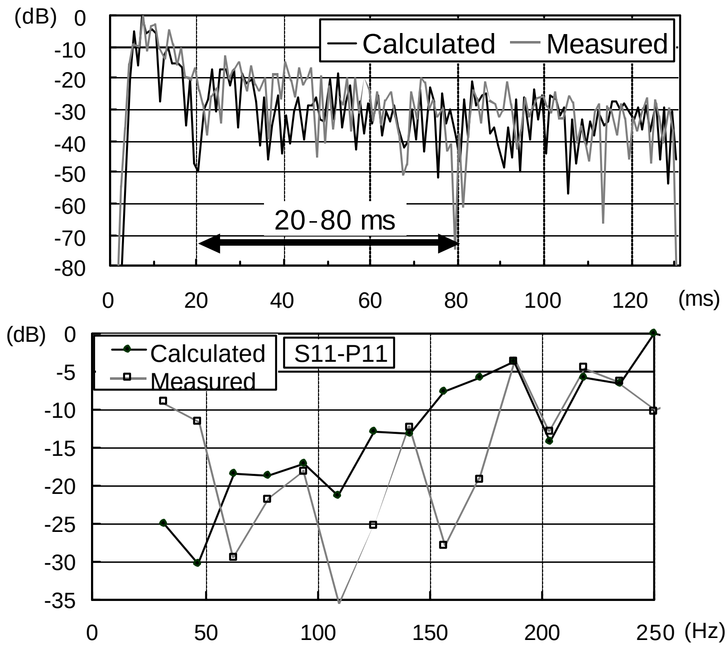

Fig. 6. Calculated and measured results
The response on the top is in the time domain and that on the bottom in the frequency domain calculated from the 20–80 ms portion of the time domain response

THE INFLUENCES OF REFLECTORS ABOVE A STAGE

Table 2 The conditions of calculated models

Model	Type R1	Type R2	Type R3
Reflector	with	without	with
Height of reflector (proscenium opening)	13 m		10 m
Stage floor	211 m^2		

In this section, the models that represent the stage area with reflectors above the stage are calculated as an example of a more complicated boundary. The conditions of the calculated models are described in table 2. The method and condition of the calculation are the same as those shown in table 1. The figure for the calculated model (type R1) is shown in figure 7. Ps and P represent source and receive positions, respectively. Type R2 has no reflector. The height of the reflectors and the ceiling in type R3 are 3.6 m lower than in type R1. The other surfaces in types R1, R2, and R3 have same conditions.

As shown in figure 8, the edge diffraction wave is recognized in the results of type R1 and type R3. Because of the locations of the receiver, source and reflectors, the diffracted wave has an opposite phase to those of direct wave and reflected waves from surfaces. In the results of type R3, the magnitude of the edge diffraction wave is strong as a reflection from other surfaces because the reflectors are nearer to the receivers in this model than in type R1. This result indicates that the edge diffraction wave from the reflector and the reflection from other surfaces are cancelled at a certain location, as shown in figure 9.

Figure 10 shows the accumulated energy curve of each type. In type R3, which has a boundary that is nearer than the others, accumulated energy is grown faster than the others. In the comparison of type R1 and type R2, the existence of reflectors does not contribute to improving the energy of early reflections.

From these results, a positive effect of floating reflectors above the stage cannot be found, but a negative effect is recognized, especially at low frequencies. This negative effect of reflectors has already been mentioned by many researchers. Here, not only are qualitative behaviors indicated but also negative influences related to other reflections are obtained quantitatively by calculating the whole stage field through wave acoustic analysis.

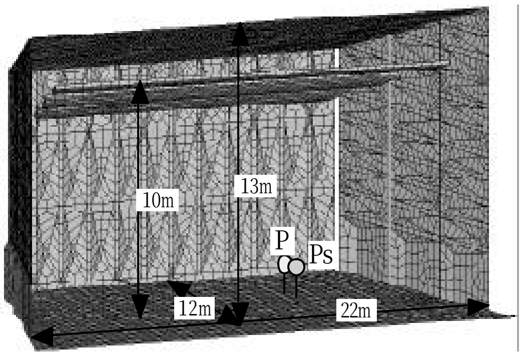

Fig. 7. Model shape (type R1)

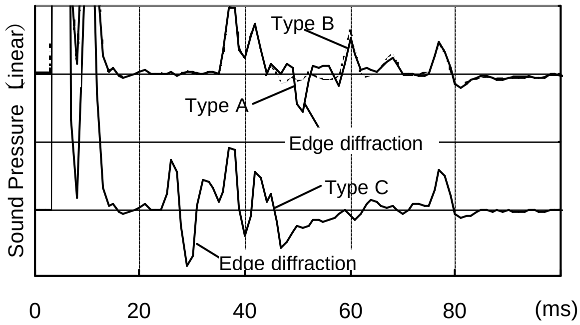

Fig. 8. Calculated results

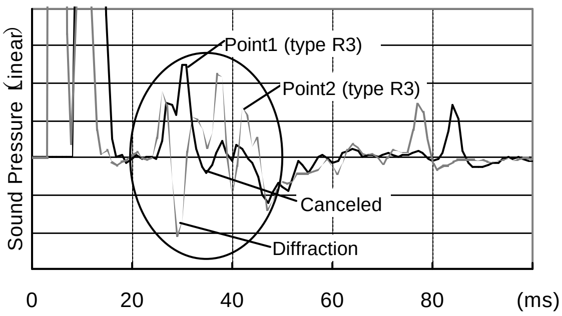

Fig. 9. Example of cancelled wave

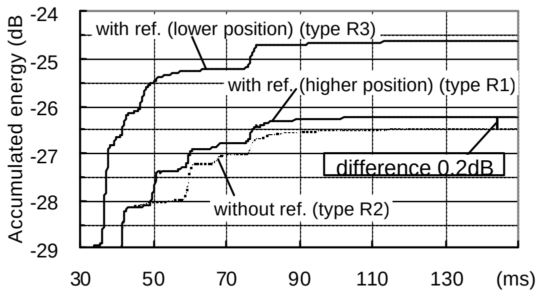

Fig. 10. Accumulated energy curve

MODELING OF ORCHESTRA PERFORMERS

When a stage sound field is evaluated, it is necessary to consider both shapes and the presence of orchestra performers in calculation models. Modeling of on-stage performers is discussed based on the results of experiments in an actual hall stage.

1. Measurement conditions. Measurements are carried out in an actual hall stage under the following two conditions: i) empty, i.e., the stage has no performers, chairs, or instruments; ii) seated, i.e., performers are seated with instruments. The locations of receive and source points are shown in figure 10. An omnidirectional speaker is set at the conductor's position and impulse responses between source point and receive points (at performers positions) are measured.

2. Influence of performers. From the difference of accumulated energy between empty and seated conditions in each 50 ms period, we found that the differences are mainly determined by a difference in diffraction due to superposing direct sound and reflection from the floor. Figure 9

shows the frequency response calculated from early parts of an impulse response, from 0 ms to 16 ms, including direct sound and reflection from the floor. Two dips occur, one at 200 Hz and the other at 500 Hz.

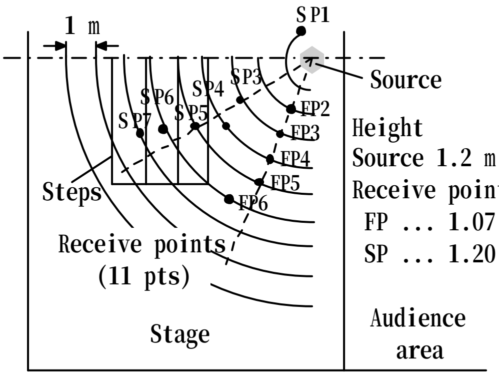

Fig. 11. Receive and source points used in the measurement

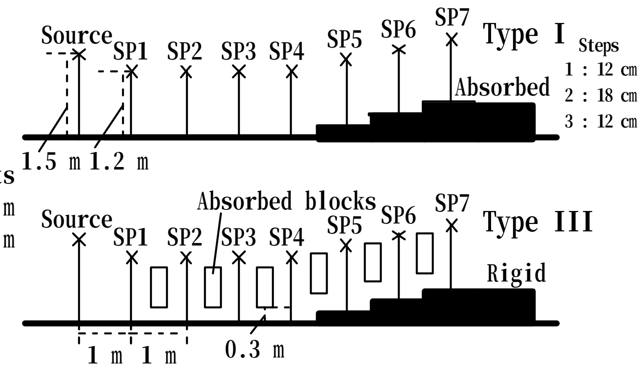

Fig. 12. Shapes of the models used in evaluating the effect of orchestra performers on stage (types I and III)
Type II with blocks without underpass

3. Models for considering performers. Based on the discussion above, we tested three types of models. Type II had absorbed blocks; type III had absorbed blocks with an underpass; and type I had no blocks but did have an absorbed floor (fig. 8). The calculated results are shown in figure 9. Type III agrees closely with the measured results. Type I also agrees for the most part but has odd dips at 200 Hz at SP5. Type II does not seem to agree. We thus concluded that type I can be used when only approximate features are needed to be evaluated and type III is suited to more precise evaluations, such as evaluating the effect of stage steps or performer arrangement.

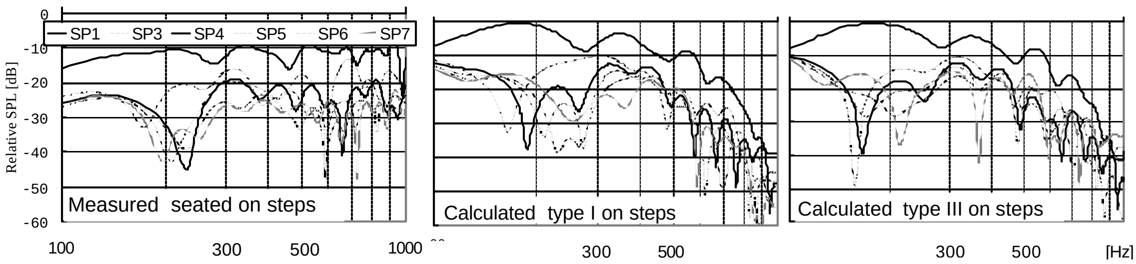

Fig. 13. Frequency response measured and calculated

We discussed modeling used to evaluate the shapes of stage enclosures using BEM and proposed models to evaluate the influence of reflectors and performers on stage. The results suggest the possibility of applying this prediction method to architectural acoustic designs.

BIBLIOGRAPHICAL REFERENCES

[1] Y. Kawai and T. Terai, “A Numerical Method for the Calculation of Transient Acoustic Scattering from Thin Rigid Plates,” *J.S.V.,*141, 83–96 (1990).

[2] J.P. Coyette, “A Refined Transient Boundary Element Method for Acoustic Modeling,” *NOISE-CON 94,* 905– (1994).