ACOUSTICAL DESIGN OF AN AUDITORIUM WITH A SEMICIRCULAR PLAN SHAPE

Takayuki Hidaka, Takehiko Nakagawa and Shin-ichiro Koyanagi
Takenaka R&D Institute, 1-5-1, Otsuka, Inzai, Chiba, 270-1395, Japan

1 INTRODUCTION

In commemoration of the centennial of the foundation of Kyushu University in 2011, the Siiki Hall was planned as a symbolic facility to serve as a new academic and cultural base of the university. The Siiki Hall is one of Japan's largest university auditoriums with a maximum seating capacity of about 2,500. The hall is originally designed to serve university events including entrance ceremonies and degree awarding ceremonies as well as academic events and lectures. After completion of the basic design, the hall was also required to be used for full-scale orchestra concerts at the strong request of the donator. The authors were invited to participate in this project after commencement of the construction work. They were asked to recommend any structural changes they found necessary to correct acoustic problems that would otherwise occur when the hall is used for musical performances. In this report, the outline of the acoustical design procedure and some innovations are reported.

2 ORIGINAL ROOM SHAPE

The shape of the Siiki hall is a near-semi circle with its center on the stage (**Fig. 1**). The architect chose this shape modeled after a Greek open-air amphitheater. The university asked for an auditorium that could be converted into a hall seating 1,000 along with five lecture halls as shown in (b) of **Fig. 2**. Musical performances could seat 1,000, as in (a) or 1,800 as in (c). The stage can have a concert enclosure (a) and (c) or a lecture enclosure (b).

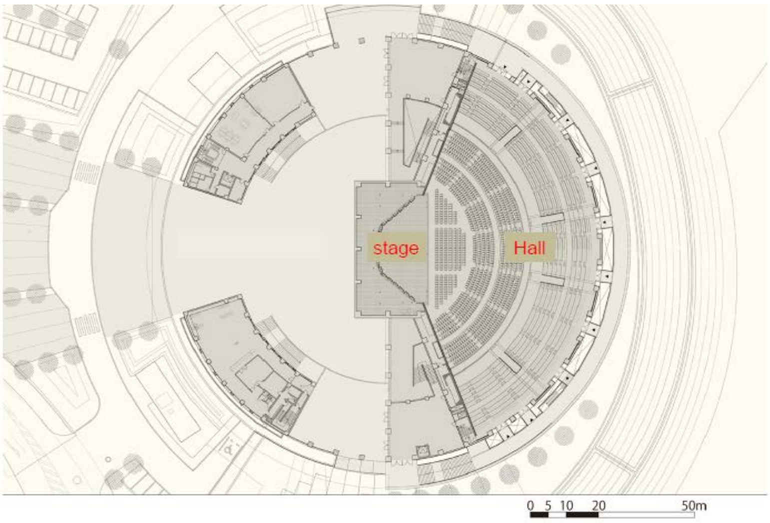
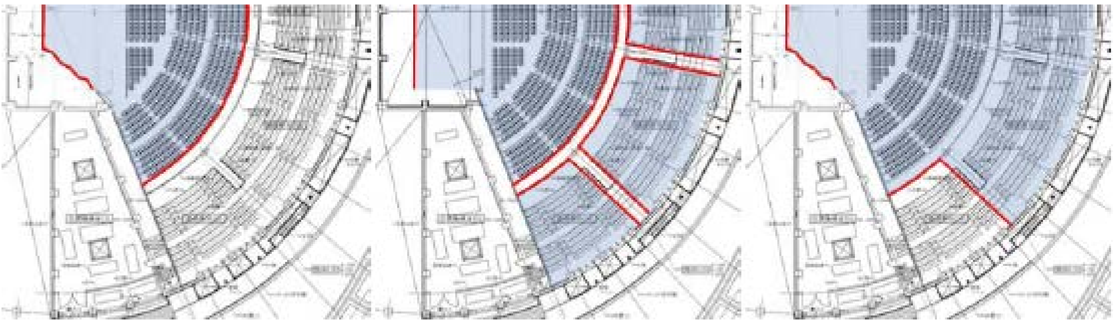


Fig.1 Original plan

Black lines in **Fig. 3** show the original floor plan and cross-section. Included are a circular sliding wall at the center aisle and a large number of sound-diffusing ceiling elements located along circular lines, A and B (**Figs. 4**). They were intended as ceiling irregularities that would diffuse the reverberant sound, but they also reflect sounds that originate at the stage end back into the front of the hall. Height of the sliding wall is 6.0 m and the widths of series of the diffusing elements at A and B are 3.1 and 2.6 m, respectively. Total lengths of these three are 63, 62, 57 m, respectively. The solution for eliminating these harmful reflections to the front follows.



(a) (b) (c)

Fig.2 Various modes of Siiki Hall: (a) 1000 seats with stage reflector, (b) 1000 seats hall w/o stage reflector and (c) 5 lecture rooms and 1800 seats hall.

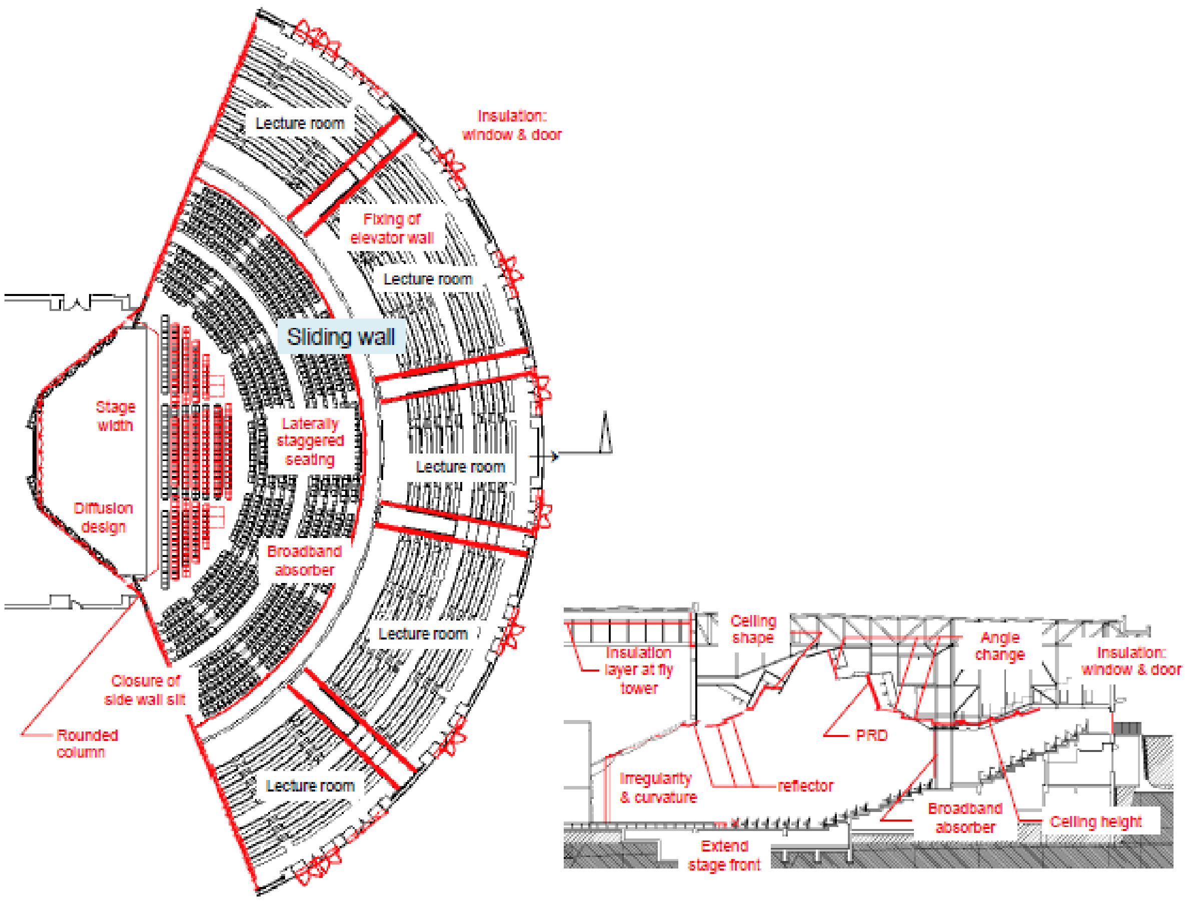


Fig.3 Red lines indicate implemented acoustic measure from acoustical reason, while black lines show original design by the architect.

3 ACOUSTICAL REVIEW

Major problems in the original design plan were as follows:

(1) The series of semi-cylinders at the ceiling positions A and B were 1.6 m in curvature radius, 2.6 m in height, and 0.8 m in depth (**Fig. 5**).

(2) Draperies were hung along the stage side of the sliding wall. They were not heavy and the space behind them was shallow so that their absorption at low frequencies was low.

Using a 3-D computer simulation, it was easily shown that the overhead and sliding wall surfaces reflected high-energy waves back to the stage and the front seats (**Fig. 6**). But the reflections from the cylinders at A and B needed more detailed analysis and this was provided by a 2-D FDTD (finite difference time domain) method. As illustrated in **Fig. 7**, it was shown that the individual reflections from the cylindrical diffusers join together to produce the same wave front in the direction of the stage as from a plane reflecting surface. From this analysis, it was confirmed that major reduction in the reflections from the sliding wall and the ceiling A and B, effective over the whole frequency range, was necessary. A 1/10 scale model was employed as the test base. The red lines in **Fig. 3** show the surfaces built into the model. In the presentation that follows only the solution to the two problems presented above are discussed.

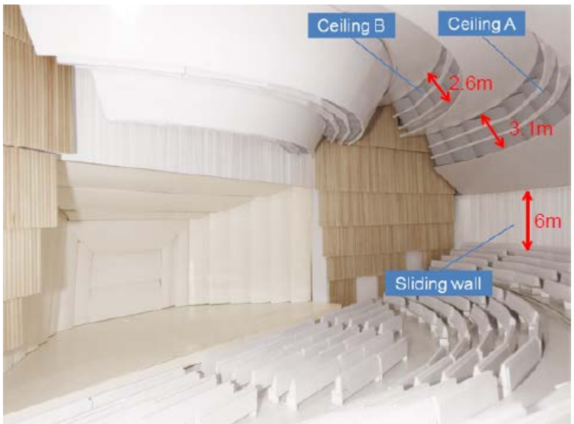


Fig.4 Original design, 1,000 seats mode. Semi-cylinders are placed onto ceiling A and B.

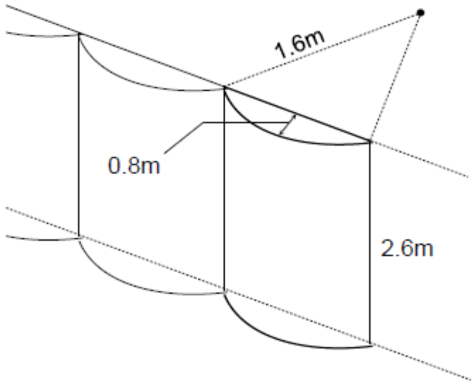
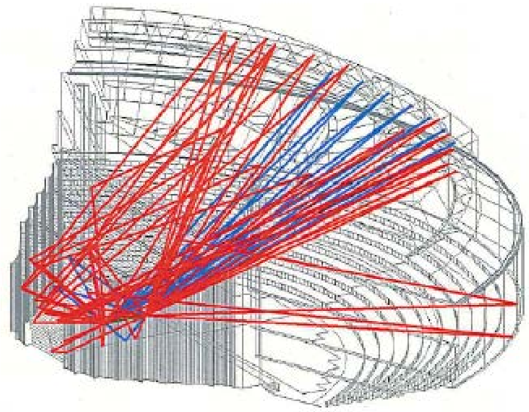


Fig.5 semi-cylinder diffusing element at ceiling walls A and B, which was planned in the original design.



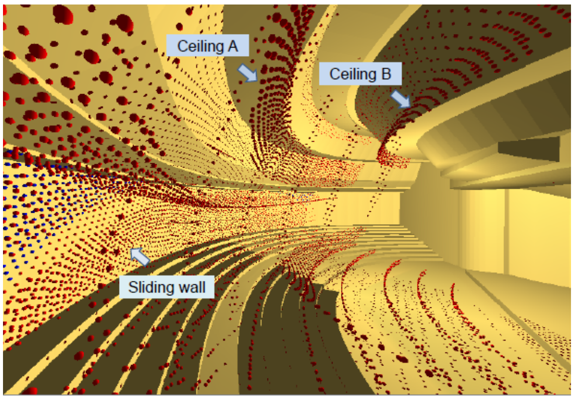


Fig.6 (Left): Ray diagram on reflection from walls and ceilings using 3-D CAD simulation. Reflections from curved ceiling are concentrated on the stage. (Right): Reflected wave fronts from ceilings A & B and sliding wall are visualized by particles.

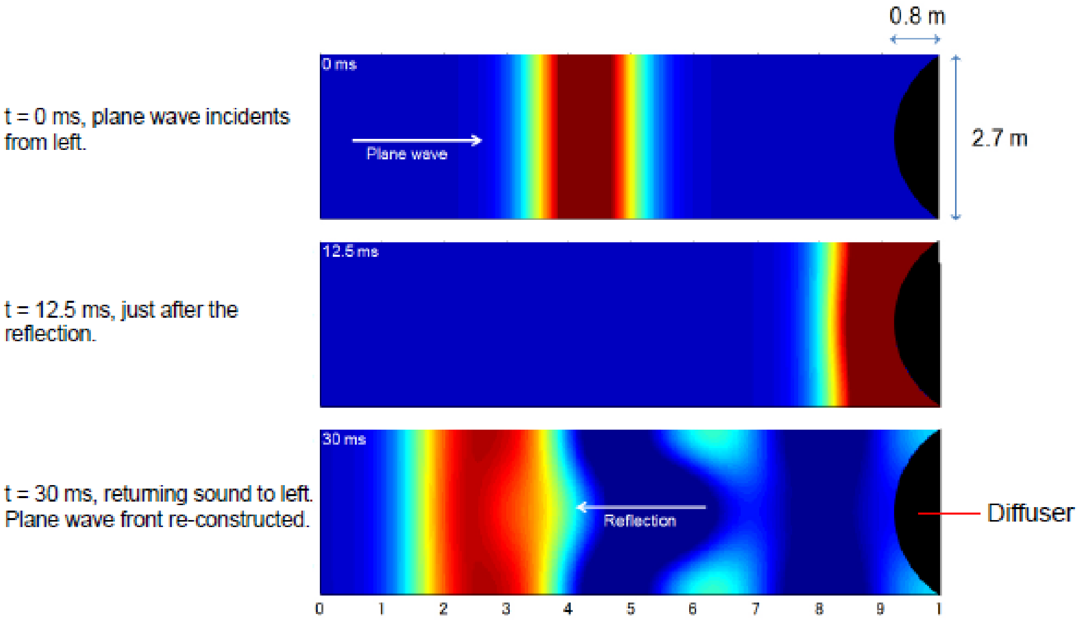


Fig. 7 Simulation of sound wave scattering with FDTD method. After a plane sound wave incidents on the cylindrical diffuser, the wave front of the reflection is almost maintained. Frequency range : DC to 125 Hz.

3.1 PRD

First, it was obvious that reducing the reflections in the direction of the stage from the ceiling A and B would have to be accomplished by some means other than adding an absorptive material which, if used, would reduce the necessary reverberation time in the hall. At ceiling A it was decided to install a PRD (primitive root diffuser [1]). The main lobe of a PRD reflects less energy in the specular direction than a QRD (quadratic residual diffuser [1]). This characteristic is more important when the incident wave arrives normally. With the PRD less sound will be reflected to the stage and the late reverberant energy will be augmented.

Theoretically, a conventionally designed PRD fails to give diffusivity at some frequencies and its performance is not well defined outside the design frequency range. Its performance was improved using a numerical analysis based on a FDTD. To confirm this result, a ¼ scale model of the diffuser was tested in an anechoic chamber. The cross-section diagram of the PRD finally chosen is shown in **Fig. 8**. To arrive at it the depth and width of the well was tweaked. The former improved the performance at high frequencies and the latter widened the effective frequency range.

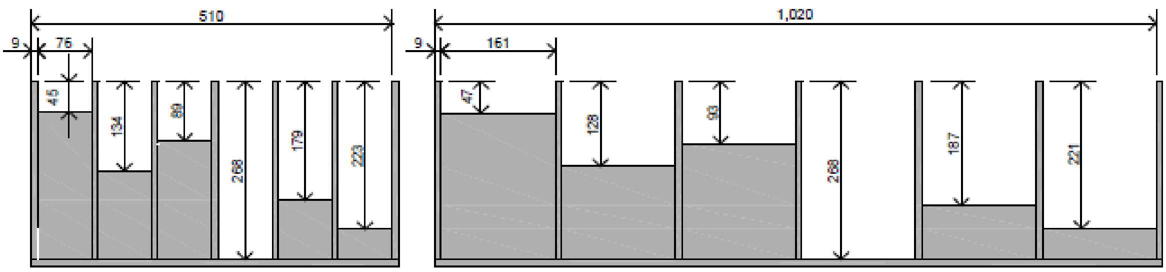


Fig. 8 Cross-section of PRD, which has different well depth and width from the conventional theory.
Left: conventional theory, Right: tweaked PRD.

The measured performance of the final PRD (**Fig. 9**) shows that it is better than the conventional PRD and a similar QRD. When installed in the hall (**Fig. 10**) the horizontal members of PRD are alternated with each set of three cycles of vertical members in order to avoid unfavorable effects caused by repetition of the same structural feature [2]. The PRD used in the actual hall was produced with volcanic vitreous double-glazed board (0.7 g/cm^3) and finished with painting.

For ceiling B, the wall surface was flat and its vertical angle was adjusted to prevent direct return of reflections to the stage or seating area. This choice was made to satisfy the limit on the weight of the building structure.

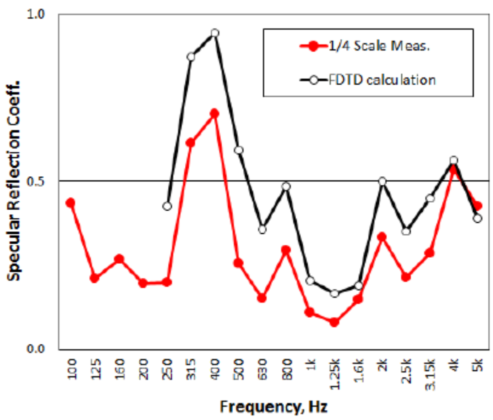


Fig.9 Specular reflection coefficient of the developed PRD for normal incidence.

Fig. 10 PRD diffuser. Actual installation in the completed hall.

3.2 Broadband thin absorber

The sliding wall along the center aisle was of greatest concern because it has the largest area (360 m^2) among three walls. It is made of steel compound panels (width 1.2 m, height 6 m, thickness 10 cm). Even without added absorption, operation of it manually is laborious. Storage space limited the thickness for additional material to *ca* 10 cm. Thus the development of a broadband absorption structure of about this thickness was necessary.

The final design for the absorbing layer is shown in **Fig. 11** and **12**. The lower layer provides bass absorption. It consists of a thin impervious membrane plus a layer of dense absorbing material. The outer layer is porous and it provides mid- and high-frequency absorption. The total panel is 11 cm thick and weighs *ca* 7 kg/m^2. When installed on the sliding wall, thin curtains were added for visual reasons.

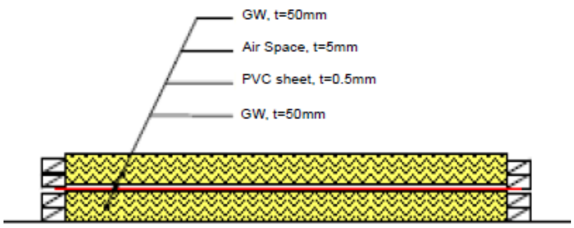


Fig.11 Cross-section structure of the developed absorber

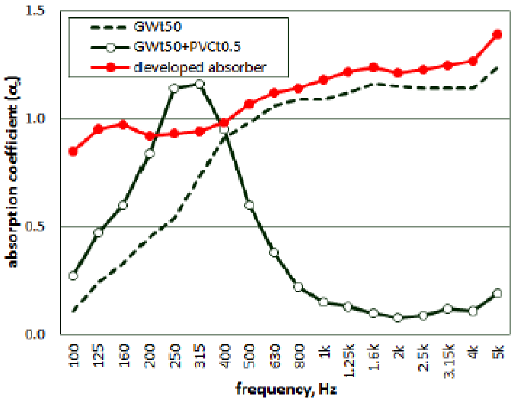


Fig.12 Reverberant absorption coefficient of the wideband absorbing panel (in red) compared with glass wool board (black broken line), and PVC sheet backed by glass wool board (black solid line).

4 SCALE MODEL EXPERIMENT

The results of the design changes were investigated in a 1/10 scale-model set up for the 1000-seat concert mode (**Fig. 13**). The structural changes shown in **Fig. 3** were incorporated and their introduction was measured step by step. The general procedure is described in [3, 4]. The reflectograms, obtained at the focal point for the ceilings A and B, are shown in **Fig 14**. The total sound energy after about 150 ms is greatly reduced as a result of adding the PRD diffuser and the absorbing layer. As shown in **Fig. 15**, the result of tilting ceiling B upward by 10 degrees was also very effective. Thus the acoustical changes measured successful.

5 AURALIZATION

A listening session designed to evaluate the results of the scale model tests was set up. Two-channel impulse responses measured at several positions were convoluted with anechoic solo and chamber music (up to 8-channel source signal) and were played back by a 2-channel stereo system in a listening room. Of course, this simulation does not include the room acoustics as a whole, but it is an effective tool for judging temporal changes in the sound field. Participants in the session subjectively confirmed the effects of the acoustic improvements.

Fig.13 1/10 scale model experiment. PRD is seen at upper right (left photo).

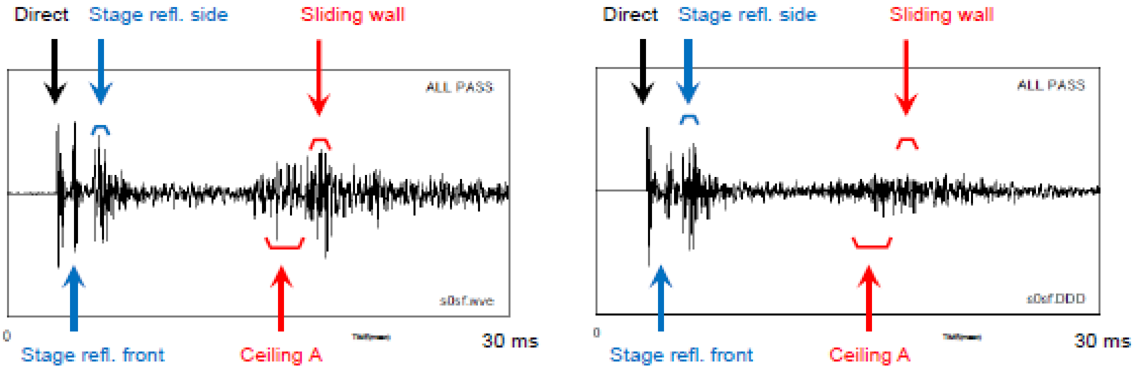


Fig.14 Reflectograms received at the focal point on stage. Frequency range is all pass, and time axis is in 1/1 scale. (left: w/o acoustical measure, right: ceiling A is covered with PRD and sliding wall is with absorption panel).

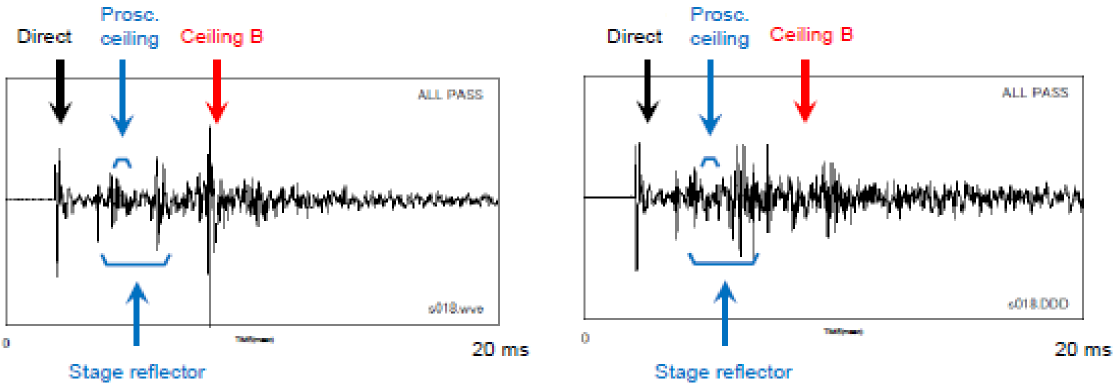


Fig. 15 reflectograms received at center seat of the main floor. (left: w/o acoustic measure, right: ceiling B is tilted upward 10 degree)

6 CONCLUSION AND PERFORMANCE AFTER COMPLETION

The acoustical measures implemented in this study that were designed to reduce sound-focusing phenomena in a semi-circular-shaped hall (**Fig. 16**) were found to be effective in the model tests. The corrections involved the above designs of the modified primitive root diffuser and the broadband absorbing panel.

At the opening concert following installation of the modifications a full orchestra performed with an audience. Members of the orchestra and the audience reported no unfavorable impressions. It is concluded that the measures undertaken in this study to correct serious acoustical problems in a semi-circular concert hall have been completely effective.

7 ACKNOWLEDGEMENT

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Fig.16 Interior view of 1000 seats with stage reflector. Broadband absorbing panel is covered by red curtain.

8 REFERENCES

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