Variable Acoustics Design of a Small Proscenium Concert Hall

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Abstract
The 403-seat Kung Hsue She (KHS) Concert Hall features a small proscenium stage designed to accommodate a wide range of performances. Attention to room acoustical design emphasized broadening the variability, while recitals by pianists and singers were considered primary. These competing purposes were realized by integrating stage curtains with the stage shell and the coupled volume outside the shell. Detached lateral reflectors were introduced to minimize sound level drop due to use of moveable curtains around the audience. The proposed design strategies were tested using a scale model and were verified in the completed hall.

Keywords: room acoustics; sound variety; small proscenium concert hall

1. Introduction
The KHS Concert Hall is a major facility at the new headquarters of the KHS Enterprise, which is one of the top five musical instrument suppliers in the world. It has become an important venue for musical performances in the Taipei metropolitan area since its opening in 2006. Although the 403-seat hall is intended mainly for recitals by pianists, singers, and other chamber music programs, there are occasions when the hall will be used for other activities. The flexibility in use as well as acoustics has been facilitated by introducing a proscenium stage and variable acoustical features.

Variable absorption and variable volume have, previously, been the principle features for multi-purpose halls (Cremer and Müller, 1982). With the combination of both, reverberation and variable sound levels can be changed to accommodate each of the several uses. Varying volume is, however, technically more difficult than varying materials. Therefore in North America it is common to build separate halls, typically with proscenium stages, differentiated in size as opposed to function (Chiang et al., 2003).

Acoustical banners are commonly used, particularly in small halls where sound level is not as critical as in a large hall. Although challenging to achieve, the effect on sound level as well as early reflections should be minimized for un-assisted music or speech. One way to realize this concept is to locate acoustical banners in the space behind the larger panel reflectors designed to direct energy, as in the Segrestroom Hall in Costa Mesa, CA, USA (Beranek, 2004). Acoustical banners are, however, not effective for low frequency absorption, even when optimized in weight, porosity, and the air space behind the banner. To provide variable low-frequency absorption, for example, the storage pockets and acoustical banners were specifically designed to fit the rear corner of the audience chamber, acting as Helmholtz resonators which were used in the Lowe San Nam hall of the, LG Arts Center at Seoul, Korea (Hoffman, 2004).

The stage shell used with a proscenium stage functions as a mechanism that simultaneously changes volume, absorption, and reflection patterns (Cremer and Müller, 1982). It provides both support to the musician and reflected sound to the main audience area (Barron, 1993). In recent decades, efforts in North America have been made to actively incorporate the stage house volume outside the stage shell as a coupled volume, if the facility has multiple purposes. The ratio of this coupled volume to the primary volume can easily reach 25% or more that is generally considered as the minimum requirement for coupled space. The fire proof coatings which are attached on surfaces of building structures, rigging system underneath the grid, draperies and scenery may affect reverberated energy (Harrison and Madaras, 2001). The upper part of the fly tower should be closed off by reflectors to reduce energy loss within this volume.
Other solutions for changing change early reflection pattern include moveable reflectors that are detached from the hall perimeters. This solution is effective, especially in those capable of providing support to the performers and lateral reflections to the audiences from above (Chiang and Huang, 1999). Movable reflectors, however, are risky to use because of the possibility of causing sound coloration or low frequency loss due to the effect of phase canceling.

Acoustical studies for the project started after the architectural firm, Yang, Chen, Architect & Associate was commissioned for the job in 2004 (Chiang et al., 2004). This paper reports on the variability of room acoustics qualities for music programs.

2. General Design Strategies

The overall size of the KHS Concert Hall was originally determined mainly according to the running cost established by the client as well as the local building law when the acoustical consultant was commissioned. The structural system was determined, too. Afterward, the hall ceiling, without conflicting with the legal requirements, was raised to 11.2 m above the stage floor, which yielded a hall volume of 3228 m$^3$. The client and the architect decided to use the same height for the rigging system, which limits the use of scenery for theatrical performances. The width of the stage and the unfinished hall was 22.7 m and 17.3 m, respectively. The overall length including the stage and the hall was 33.1 m. Fig.1. shows a longitudinal section and plan drawings for the KHS Concert Hall.

2.1 Design considerations

The proscenium width was set to 14.0 m. A fixed wall 2.2 m from the structural rear wall of the stage and 10.0 m from the front edge of the stage floor was used as the shell rear wall. The moveable shell side walls were splayed at an angle of approximately 12.5°. The total available performing area for an ordinary shell setting is about 106 m$^2$. An enlarged shell setting yielding an area of 120 m$^2$, sufficient for a small orchestra is also possible.

With the small size of the stage house and accommodation of music programs being the primary concerns, it was possible to use the volumes above and on the two sides of the stage shell as coupled volumes. By setting the average shell height set to 6.8 m, the coupled volume left over in the stage house became 2428 m$^3$, comparable to the 3949 m$^3$ primary volume including the hall volume and the volume enclosed by the shell. The primary volume and the coupled volumes were coupled with apertures at three locations, one between the moveable shell ceiling and a fixed extension of the shell ceiling, another between the extension piece and the hall ceiling, and the other between the fixed shell rear wall and the shell side walls were. Thick leg and border curtains were used as economical solutions to provide variable acoustical features to adjust sound absorption of the coupled space. With no side boxes being used, it left ample wall areas for installing variable absorptive materials.

Movable curtains with effective variable of area about 78 m$^2$ were designed to compensate for the difference in sound absorption of the hall space between occupied and unoccupied audience conditions. Four triangular shaped lateral reflectors detached from the hall surface were proposed to mitigate the early energy loss, especially in high frequency when the curtains were lowered. Each reflector was composed of four smaller pieces to form a convex surface. The locations of the reflectors at the upper, side corners of the halls approximately covered the main directions for sounds from higher strings, wood winds and singers...
which are radiated towards the audience, allowing for emphasis either to the side walls or to the ceiling. Fig.2. shows the front view of the completed KHS concert hall. Surface diffusivity was realized by the cylindrical arrays on the stage shell, the angled arrays of broken surfaces on the ceiling, and the molded two dimensional diffusive elements on the side walls.

Fig.3. Simulated 1st Order Reflection Coverage from One Side of the Proposed Lateral Reflectors

The Odeon 5.0 software package was used to validate the schematic concept of using the triangular reflectors (Clause, 2001). Double layers of gypsum board and a 0.1 scattering factor were assigned to the side and rear walls. The geometrical details of the hall and the stage house, for example the concrete beams and coffers around the stage, were not considered. Occupied seating with medium upholstery was used for the audience and a 0.7 scattering factor was assigned. As shown in Fig.3., the coverage of 1st order reflections can be evenly distributed to the audience beyond the critical distance of approximately 6 m by only one side of the proposed lateral reflector.

3. Design Development and Scale Model Testing

A 1/30 scale model was tested towards the end of the design development phase for detailed analysis to accounted for sound diffusion and diffraction. The directional pattern for the scaled-up frequency range of the sound source, a Grozier GTS51 high-voltage electrical spark, was considered similar to a human speaker. The signals were recorded using a B&K 4138, 1/8 inch microphone and were converted into digital data at a sampling rate of 240 kHz using a Burr-Brown ZPB34 board installed on a personal computer. The Hypersignal-Acoustic software package was used to handle data acquisition and octave-band based signal processing. The Environmental Research Group, at the National Taiwan University of Science and Technology developed the associated macro programs. The impulse response was derived from four repeated measures of the spark sources to increase signal-to-noise ratio. Seven microphone receivers at the audience area were used with the sound source placed on the central axis and 2-m from the front edge of the stage floor (Fig.1.).

Fig.4. The Images of Four Coupling Configurations on the Stage

Early decay time (EDT) (the time for sound to decay 60 dB based on the first 10 dB portion of the decay), reverberation time ($T_{30}$) (the time for sound to decay 60 dB based on the decay from -5 dB to -35 dB), and sound strength (G) (the logarithm ratio of the total acoustical energy to the energy measured 10-m from the same source) were calculated using the B&K Dirac software package in accordance with ISO-3382 standard.

Concrete walls and floor slabs were made of 12-mm plywood. The hall ceiling panels were made of 1-mm acrylic panels. The walls were made of 2-mm cardboard with the diffusive elements molded using hard plastic. The cylindrical stage shell surfaces and the lateral reflectors were made of 1.2-mm white cardboard. The empty audience chairs were made of thin cloth on 30-mm polystyrene foam boards. The mid-frequency absorption coefficient was 0.79 when measured in the hall model, a value close to the published data of occupied audiences with medium upholstered seats measured in actual halls. The theater curtain was represented by thin cloth with a 10-cm (scaled down dimension) air space behind it. Mid-frequency and 125-Hz band absorption coefficients were around 0.9 and 0.2, respectively.

3.1 Coupling the hall with the stage house volume

The configuration of the stage with all coupling apertures being sealed (designated as configuration SS) was compared to three other configurations, one with the apertures open (configuration SO), another with 300-mm gaps between individual shell ceiling pieces (configuration SG), and the other with the shell size enlarged (configuration SE). The aperture for the ordinary size shell was about 64.2 m$^2$, i.e., the area of paper boards used to seal the apertures, and was increased to 80.9 m$^2$ for the enlarged shell. Fig.4. and Fig.5. shows the images of the four coupling
configurations.

Fig. 6. shows the reverberation time ($T_{30}$) and early decay time (EDT) derived from the model testing. Reverberation time averaged from 250 Hz through 2 kHz, and was increased by approximately 21% when the apertures were changed from sealed (configuration SS) to opened (configuration SO) conditions. Little difference in $T_{30}$ was found among the 3 configurations with the stage volume coupled. EDT averaged from 250 Hz through 2 kHz was increased by 7% with the apertures opened and was further raised by 4% when the stage shell was enlarged. The change in EDT can be attributed to the apertures that are large enough and are located near the surfaces that provide early reflections. The 300-mm gaps, however, had little effect on either $T_{30}$ or EDT.

As shown in Fig. 7., the decay curves measured at position 7 of the configurations with the apertures sealed (dashed line) and opened (thin line) separated after 3-dB of decaying and were further apart from each other after 8-dB of decaying. The energy decay was slowed down early enough to slightly increase early decay time when the shell was opened. The much slower decay rate starting from the very beginning by enlarging the shell can be attributed to the longer reflection paths from the shell surfaces.

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The effect on initial decay supported the idea of providing greater variability in both $T_{30}$ and EDT by deadening the coupled volume using stage curtains instead of sealing the apertures. As shown in Fig. 1., the projected area of these curtains was 278 m².

A 121-m² rear curtain was also introduced to further reduce early reflected energy for percussion groups or any other music programs that use assisted sounds. Fig. 8. shows reverberation time ($T_{30}$) and early decay time (EDT) derived from scale modeling illustrating the effect of the stage curtains. When introducing legs
and borders, both $T_{30}$ and EDT were shorter than the values derived from the configuration with the shell sealed. The influence of these curtains in the coupled volume was, however, more significant for $T_{30}$. Further applying the rear curtain yielded average EDT and $T_{30}$ (averaged from 250 Hz through 2 kHz) near 1.0 s and 1.1 s, respectively.

The scatter plot in Fig. 9. illustrates the relations between sound strength ($G$) and early decay time (EDT) for the situations utilizing the coupled volume around the stage shell. The theoretical relation between EDT and $G$ with varying sound absorption is shown by the solid line. By coupling the stage volume, $G$ values decreased with increasing EDT, similar to what can be derived by increasing the hall volume. An even lower $G$ value could be derived by further enlarging the shell as well as the apertures. When applying legs and borders where both early and late energy were being suppressed, the measured $G$ agreed with the theoretical value indicated by the solid line. The value was only 0.5 dB less than the configuration with no curtains inside the coupled stage and 0.9 dB less than the configuration with the shell sealed.

### 3.2 Varying reverberation with features on the audience side of the hall

Fig. 10. compares reverberation time ($T_{30}$) and early decay time (EDT) comparing the hall with (filled marks) to without (open marks) hall curtains and with ($\Delta$) to without (O) the lateral reflectors. Lowered and the reflectors installed, the reduction in averaged EDT from 250 Hz through the 2 kHz band was about 13%. The reduction was also spectrally balanced.

With no lateral reflectors, lowering the curtains caused a significant drop in sound strength ($G$) for the remote seats (Fig. 11.). The average sound strength difference was greater than the theoretical estimate based on the EDT difference of the two hanging conditions of the curtains. Introducing the reflectors mitigated the energy drop by providing early, lateral reflections. The average sound strength drop (averaged from 250 Hz through 2 kHz band) was reduced from 1.2 dB to 0.6 dB.

Fig. 12. shows the envelopes of log-squared 1-kHz band impulse responses for the microphone receiver 7 (R7 in Fig. 1.) illustrating how the effect of the hall curtains was influenced by the lateral reflectors. With no reflectors, the pattern of the early reflections with the curtains lowered was similar to the pattern with the curtains raised, yet with amplitude reduced by 1.7 dB. The lateral reflectors provided reflections starting 22 ms after the direct sound, reducing the energy drop to 0.8 dB when the curtains were lowered.

### 4. The Completed Hall

Measurements were taken in the completed hall using the B&K Dirac software system. A linear sweep sine wave was played through a Norsonic 223 dodecahedron speaker. At a height of 1.2 m, a B&K 4192 microphone was used to record the monaural signals. The fixed rear wall of the shell and the hall ceiling were constructed of 24-mm gypsum board. The molded diffusive elements on the side walls were made of fiberglass plaster with thickness in the range of 20 mm to 90 mm. The stage curtains and the moveable hall curtains were typical 16 oz and 32 oz theater draperies, respectively.
Unoccupied reverberation time data are tabulated in Table 1. Without using the rear curtain, the maximum difference in mid-frequency reverberation time for all configurations using the stage shell was 0.28 s. Although not as great as studied using the scale model due to some absorption at the stage, this range is enough for a variety of chamber music programs. For percussion in particular, hanging the rear curtain could provide an extra reduction of 0.2 s. For orchestra programs which are rarely expected, the reverberation time can be slightly raised by removing the traveler curtains from the track. Incorporating the curtains with the lateral reflectors and the coupled volume provided rather uniform variability across the 6 frequency bands while using only curtains, sorely, would result in excessive absorption at high frequencies yet insufficient absorption at low frequencies. This can be demonstrated by the small reverberation time reduction in the 125 Hz band when hanging the rear curtains (Table 1.).

The coupled room effect was not clearly observed except at low frequencies for the configuration with the shell enlarged, because of the spray-on absorption on the steel beams of the stage ceiling. This can be illustrated by the decay curves shown in Fig.13. The double slope characteristics can be easily identified in the 125-Hz band curve (the thick, solid line) for the configuration with the shell enlarged.

5. Summary

The proscenium stage of the KHS Concert Hall reserved for occasional theatrical use provided the chance of coupling the stage space for music programs where longer reverberation are required. The stage curtains, on the other hand, as well as the moveable curtains in the hall were used as economical solutions to provide variable absorption features. Scale modeling was employed as the principal tool for detailed acoustical analysis.

The results generally demonstrated the possibility of incorporating the stage volume with the stage curtains to provide a reasonable range of variability that independent from frequency and strength. The apertures around the proscenium and at the rear end of the stage shell were large enough to allow the reverberant energy from the stage space to influence both early and late portions of the decay. It was also found that spectrally unbalanced absorption of the...
moveable curtains in the hall could be mitigated by integrating the curtains with triangularly-shaped lateral reflectors. The reflectors were also effective in directing early, lateral reflections to the remote seats where acoustical energy would be dissipated by the curtains otherwise, especially when considering the directional characteristics for higher strings, wood winds, and vocal sounds. Little change in sound strength (G) was found for any of the proposed schemes.

With the presence of stage shell, the unoccupied mid-frequency reverberation time (T\textsubscript{30}) measured in the completed hall is in the range of 1.2 s to 1.7 s. The spectrally balanced variability in reverberation was also verified.

Table 1. Tabulated Reverberation Time (T\textsubscript{30}) Measured in Unoccupied Hall

<table>
<thead>
<tr>
<th>Octave band center frequency (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1 k</th>
<th>2 k</th>
<th>4 k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enlarged shell, no stage curtains, audience banners raised</td>
<td>1.97</td>
<td>1.72</td>
<td>1.68</td>
<td>1.69</td>
<td>1.57</td>
<td>1.44</td>
</tr>
<tr>
<td>Ordinary shell, no stage curtains, audience banners raised</td>
<td>1.89</td>
<td>1.69</td>
<td>1.64</td>
<td>1.65</td>
<td>1.57</td>
<td>1.43</td>
</tr>
<tr>
<td>Ordinary shell, legs and borders on stage, audience banners raised</td>
<td>1.79</td>
<td>1.57</td>
<td>1.53</td>
<td>1.54</td>
<td>1.48</td>
<td>1.36</td>
</tr>
<tr>
<td>Ordinary shell, legs and borders on stage, audience banners lowered</td>
<td>1.71</td>
<td>1.49</td>
<td>1.40</td>
<td>1.41</td>
<td>1.36</td>
<td>1.36</td>
</tr>
<tr>
<td>Ordinary shell, legs and borders on stage, audience banners lowered, rear curtain extended</td>
<td>1.65</td>
<td>1.34</td>
<td>1.19</td>
<td>1.22</td>
<td>1.18</td>
<td>1.09</td>
</tr>
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References