Acoustical design of the Tokyo Opera City (TOC) concert hall, Japan[a)]

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The Tokyo Opera City concert hall seats 1632, volume 15 300 m^3, and reverberation time, with audience and orchestra, 1.95 s. As part of the design process, measurements on CAD computer and 1:10 wooden models of the hall and full-sized materials samples were conducted over a 5-yr. period. The hall in plan is rectangular. The ceiling is a distorted pyramid, with its peak 28 m above the main floor and nearer the stage than the rear of the hall. This unique shape was analyzed on the models so that all interior surfaces combine to distribute sources on the stage uniformly over the seating areas and to yield optimum values for reverberation time (RT), early decay time (EDT), interaural cross-correlation coefficient ($IACC_{E3}$), bass ratio (BR), initial-time-delay gap (ITDG), strength (G), and sound diffusion index (SDI) [for definitions see L. Beranek, *Concert and Opera Halls: How They Sound* (Acoustical Society of America, Woodbury, NY, 1996)]. On the long ceiling facing the stage, Schroeder QRD diffusers provide diffusion, eliminate a possible echo, and strengthen lateral reflections. Performers and critics judge the acoustics excellent. [S0001-4966(00)00101-6]

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INTRODUCTION

The Tokyo Opera City complex (TOC) is contiguous with the New National Theatre complex (NNT). The NNT is on a 6-acre site and consists of an opera house, drama theater, experimental theater, and many other spaces. The TOC involves 5 acres on which are located the concert hall, rehearsal and education spaces, a 54-story sky-scraper, an art museum, and an arcade with shops and restaurants. A multilevel garage underlies the entire 11-acre site.

Nine Japanese companies own the property on which TOC is built. They formed the ''Owners Council of Tokyo Opera City Project,'' and named an Executive Committee to oversee the design, construction, and operation. Because of the size and diversity of buildings, a joint-venture design team was assembled by the Executive Committee, and Takahiko Yanagisawa of TAK Associated Architects was commissioned as the lead architect for the concert hall. [See the *Architects Preface* in the companion paper on the NNT opera house (Beranek *et al.*, 2000).]

Composer Toru Takemitsu was first commissioned as musical consultant and later as artistic director of the concert hall. Sadly, he died before completion and the concert hall is now designated the *Takemitsu Memorial*.

The requirements presented to the Acoustical Consultants by the Executive Committee and the Architect were (1) the hall should seat approximately 1630; (2) it must be planned primarily for concerts and recital performances; and (3) its reverberation time should lie in the range of 1.8–2.0 s with full occupancy. Several designs were produced by the architect before 1991, all of which had wooden side walls and ceiling.

Beranek was commissioned as the Acoustical Design Consultant for the TOC concert hall in April 1991. The acoustical staff of the Takenaka R&D Institute of Chiba, Japan, headed by Hidaka, was retained to make models and perform all necessary acoustical measurements. The first move was to review throughly the technical literature on concert hall design. Notable work in the past 30 years has come from Goettingen and Berlin in Germany, New Zealand, England, Canada, Denmark, Japan, and USA. [A summary and references are given in Beranek (1992).] Eight acoustical parameters, six of which are orthogonal, were identified as contributing to acoustical quality.

Hidaka and staff made modern acoustical measurements on 23 halls in Europe, Japan, and the Americas. Simultaneously, a systematic effort was accelerated to complete the assembly of drawings, photographs, details on materials, and acoustical data for 66 concert halls in regular use in 22 countries. Beranek (1996) determined, from interviews of qualified listeners, rank orderings of 34 concert halls for which binaural acoustical data were available (see Table I of Hidaka *et al.*, 1995), and by correlation determined an optimum range for each of the six orthogonal parameters and produced charts for combining the measurements on them into a physical rating scheme adapted from a procedure proposed by Ando (1985).

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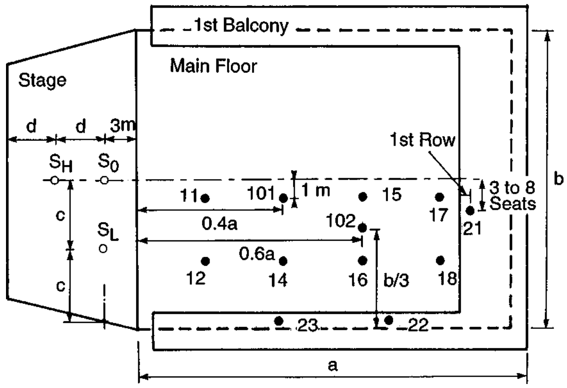

FIG. 1. Measuring positions used by the Takenaka R&D Institute group. For symmetrical halls, the measurements are generally made at least at the eight positions shown, and at more positions if there are more balconies or if there are a number of terraces. The letters a–d relate to the dimensions of the hall and determine the locations of sources and receivers. For three source positions and nine receiver positions, this gives 27 observations on the main floor. Each balcony or ring chosen has three or more positions.

I. ACOUSTICAL MEASUREMENTS

In all of the acoustical measurements made in 23 halls, a dodecahedral sound source was placed on the stage at one to four positions shown as examples in Fig. 1, of which S_0 was used in every hall. Each sector of the dodecahedral sound source, with a loudspeaker, is 21.5 cm on a side. For the binaural measurements in the halls, standard ''dummy'' heads fitted with microphones in the ear canals, or persons with two tiny microphones taped to the entrance of the ear canals (Fig. 2) were employed. The wearer of the microphones recorded their output on a DAT recorder. Accuracies of this kind of measurement were covered in Hidaka *et al.* (1995).

A modified stretched impulse signal was used (Aoshima, 1981) as shown in Fig. 3. The interaural cross-correlation functions corresponding to the measured impulse responses were calculated in the laboratory using the Wiener–Khinchin theorem (IEEE, 1979). Using a synchronous summation technique, a sequence of ten stretched pulses was recorded to improve the S/N ratio. The recorded signal is also the timing signal for starting the A/D conversion, which is possible by starting the stretched impulse with a lower frequency component than that specified by Aoshima. With a high-frequency component such a timing signal is not possible because of the waveform distortion at the impulse's beginning, which is apparently caused by phase fluctuations that modulate the refraction index of air.

FIG. 2. Subject wearing miniature microphones at outer ear canals and DAT recorder in his lap for binaural measurements at audience positions.

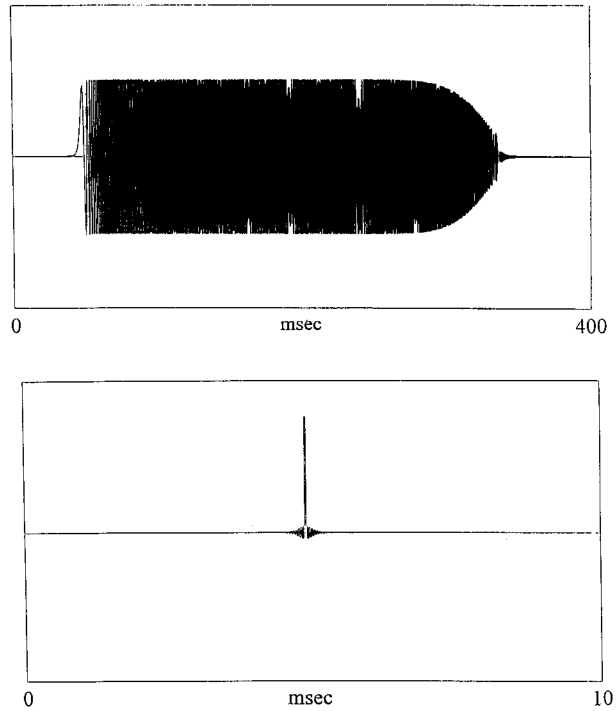

FIG. 3. (Upper) Waveform of the stretched impulse signal, $s(t)$. (Lower) Waveform of the exact impulse, $FT^{-1}[\exp[-B]\cdot FT[s(t)]$, compressed by the phase shift filter.

Seven acoustical parameters were measured in eight frequency bands by these techniques: RT, EDT, $[1\text{-IACC}_E]$, C_{80}, BR, ITDG, and G (definitions are given in the Appendix). An eighth important acoustical parameter has not yet received an approved physical measurement, and must be estimated from visual inspection, namely, the sound diffusion index SDI. Diffusion of the sound field is produced by the architectural irregularities on both the ceiling and side walls of a hall, both large and small in scale. The correlations among the objective acoustical factors measured in the concert halls are listed in Table I. It is seen that RT_M and EDT_M are highly correlated and that $C_{80}(3)$ is also highly correlated (negatively) to these two parameters. The other acoustical parameters have low correlations among themselves and with RT_M, EDT_M, and $C_{80}(3)$. Obviously, SDI has low correlation with the other factors.

II. DESIGN PROCEDURE

In May 1991, the architect presented preliminary drawings which showed a hall whose lower part was rectangular in shape. The upper part was a distorted pyramid whose base started at the lighting trough which is located above the second balcony. The acoustical design process involved three stages from that time to the opening of the hall. First, a computer simulation of the hall was programmed. With it, ray traces through the second reflection, including air attenuation and diffraction from reflecting surfaces, was used to determine the feasibility of a rectangular/pyramidal shape

TABLE I. Correlation coefficients among objective acoustical factors calculated from the results of measurements in 39 concert halls. The subscripts ''M'' and ''3'' mean, respectively, that the octave band average was for 500 and 1000 Hz, and 500, 1000, and 2000 Hz. The significant correlations are in **bold** type.

	RT_M	EDT_M	$C_{80}(3)$	G_M	1-$IACC_{E3}$	BR	ITDG	V	N
RT_M	1.00								
EDT_M	**0.99**	1.00							
$C_{80}(3)$	**−0.84**	**−0.87**	1.00			**Bold**:>0.6			
G_M	0.31	0.31	−0.34	1.00					
1-$IACC_{E3}$	0.17	0.20	−0.37	0.46	1.00				
BR	0.08	0.04	0.04	0.04	−0.16	1.00			
ITDG	−0.48	−0.50	0.57	−0.43	−0.13	−0.04	1.00		
V	0.27	0.23	−0.03	−0.55	−0.51	0.21	0.25	1.00	
N	0.11	0.09	0.05	−0.53	−0.55	0.29	0.18	**0.84**	1.00

and the approximate values of the acoustical parameters. Second, a 10:1 wooden scale model of the hall was constructed as soon as the broad design was set, in which the shaping of reflecting surfaces, the height necessary to achieve the desired reverberation times, and the values for acoustical attributes were set. Third, after construction of the hall and several months before the opening, a test concert, with invited orchestra and audience, was arranged to determine the balance among the sections of the orchestra, whether the musicians heard each other well, and whether there were any peculiarities in the sound in the audience areas or on stage that had not been detected in the 10:1 model.

III. NUMERICAL CRITERIA AND INITIAL DECISIONS ADOPTED IN 1991

Reverberation time, $\mathbf{RT_M}$, **and early decay time**, $\mathbf{EDT_M}$: RT_M is the average of the RTs at 500 and 1000 Hz, with full audience and orchestra. For the nine halls rated highest in the survey of conductors and music critics (Beranek, 1996, Table 5.2; Hidaka *et al.*, 1995, Table I) the average reverberation time is 1.9 s, with a range from 1.8 to 2.0 s. It was agreed that the goal for RT_M would be 1.9 ± 0.1 s. In very good to excellent halls, the EDT_M (measured when unoccupied) is on average about 0.5 s longer than RT_M (measured when occupied). Previous experience has been that EDT is more critical in setting the acoustical quality of a hall for music than RT, but that if either the energy or the decay time in the RT portion of the sound decay is too low, the hall will lack the highly desirable ''singing tone'' of halls like those in Amsterdam, Boston, and Vienna. EDT is highly correlated with RT in all halls except for those of unusual shape or with addable volumes.

Shape: Because 6 of the highest rated halls in the 34 hall list in the two references above are shoebox shaped, a rectangular shape for the lower part of the TOC hall, which includes the main floor and balconies, was immediately judged acceptable. The unique pyramidal shape for the upper part of the hall, proposed by the architect, did not appear to present an insurmountable problem if proper diffusion and echo control were incorporated. This, of course, needed confirmation in the models.

Intimacy: The attribute that causes listeners to feel, acoustically, that they are in close contact with the performing group, is measured by the initial-time-delay gap, ITDG. Because the seating capacity is 1632, and the width of the hall is about 20 m, the resulting ITDG, at mid-main floor, is about 15 ms, well below the maximum acceptable value of 25 ms.

Spaciousness is defined as the combination of (a) subjective acoustical width of the performing body (called ASW, the apparent source width), and (b) the listener's feeling of being surrounded by the reverberant sound field (called LEV, listener envelopment). The rectangular shape is perfect for achieving the desired ASW provided all sound reflecting surfaces are properly oriented to yield a high measured value of $[1-IACC_{E3}]$. For the best halls this parameter exceeds 0.6. In regard to LEV, listeners feel surrounded by the reverberant sound if there is an unobstructed volume above the balconies, the RT is large enough, and there is adequate large-scale diffusion in the room [see Hidaka *et al.* (1995) and Okano *et al.* (1998)]. There is no agreed-on physical means for measuring LEV.

Clarity, $\mathbf{C_{80}(3)}$, is highly (inversely) correlated with the early decay time EDT_M when the initial-time-delay gap is short and there are a number of reflections between it and 80 ms. In the best concert halls, the measured $C_{80}(3)$ (unoccupied) is between −1.0 and −4.0 dB (Beranek, 1996, Tables 5.2 and 12.1). The goal is a value within this range.

Diffusion, sound index, SDI is defined as the homogenizing of the sound field produced by irregularities on all reflecting surfaces. The halls most highly rated subjectively have highly irregular side walls and ceiling. One of the basic acoustical problems in the ill-fated Philharmonic Hall in New York was the lack of irregularities on any of the sound reflecting surfaces (eliminated for budgetary reasons). Diffusion must be of two types, fine scale and large scale. In the TOC it was decided to recommend fine-scale diffusion on the side walls beneath the balconies and large scale diffusion on the balcony fronts and the ceiling. Haan and Fricke (1993) have shown SDI to be a primary acoustical parameter for concert halls. No objective measurement has been standardized, so SDI is presently judged visually.

Strength G has been shown generally to be related to the ratio of (a) the early decay time EDT to (b) the cubic volume of the room (see Beranek, 1996, p. 445). In this hall with a seating capacity of 1632, this ratio will be similar to that in Vienna and Zurich if the desired EDT is achieved. The design problem is to make the SPL as uniform throughout the hall as possible.

Bass ratio, BR, is the ratio of the average RT at 125 and 250 Hz to RT_M. From measurements in the best halls, it was found that BR should exceed 1.0 (Beranek, 1996, Table 8.5).

Over-stage reflector: The sound radiated upward by an orchestra must be captured and reflected in part to the front portion of the audience area on the main floor and in part to the musicians on stage. In the TOC hall, because of the pyramidal ceiling, an overhead reflector is absolutely necessary to achieve these purposes.

Stage floor: A satisfactory stage floor must be wooden and not too thick or overly braced if it is to augment the vibrations of the pins on the cellos and basses.

Stage enclosure: Experience has shown that there should be sloping reflecting surfaces around the three sides of the stage, not far above the heads of the players, so that the players at the extreme sides of the orchestra can hear the music of the others. Further, the side (end) walls of the stage enclosure should be splayed, so as to send sound energy toward the audience and not to confine it to the stage alone. This is especially important for small orchestral groups and recitals. It was also decided that the area of the stage should not be too large, because if it is as wide as in many contemporary halls, the players cannot maintain good ensemble. For chamber groups and recitals, a large stage is a definite disadvantage. It was decided to make the stage area 10% larger than that in Boston Symphony Hall, which has been adequate there for nearly a century. Of course, if the stage area is thus limited, it needs to be extended for large choral works.

Seats and carpets: Because the interior surfaces of the TOC hall are of wood, which, even though 25 mm thick with a mass of 40 kg/m^2, absorb more bass than plaster walls, the audience seats must be chosen to absorb less bass. No added absorbing materials, including carpets, can be permitted.

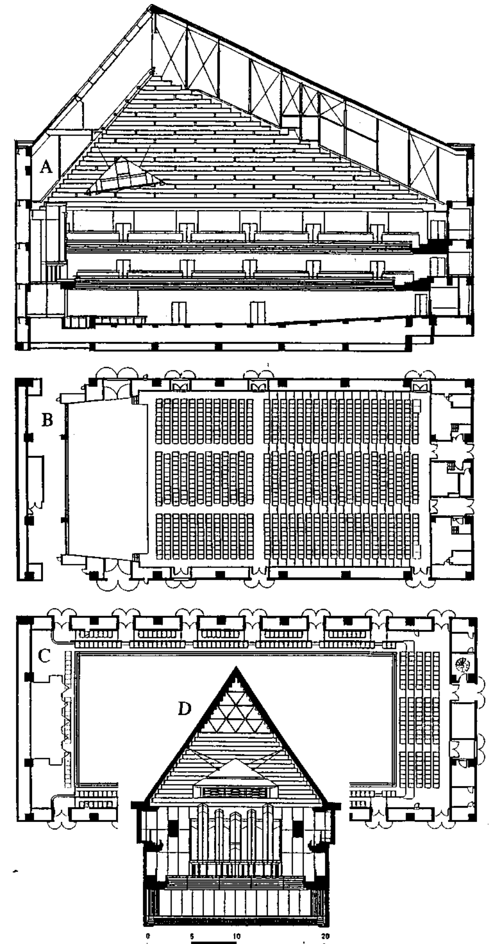

FIG. 4. The TOC concert hall as built: (a) Longitudinal cross section. (b) Main floor. (c) First balcony. (d) Lateral cross section at highest ceiling point. The second balcony is similar to the first, except it has three rows of seats at the rear. Many variations were presented originally by the architect for acoustical evaluation. Architect: Takahiko Yanagisawa, TAK Associated Architects, Tokyo.

IV. COMPUTER AND 10:1 WOODEN SCALE MODEL TESTS

By February 1992, the Takenaka Laboratories had completed both the computer model and the 10:1 wooden model of the TOC concert hall. With the 10:1 model, not only could the acoustical attributes listed above be measured, but the sounds of the hall could actually be heard, which is especially valuable for detecting echoes. The principal limitation with a 10:1 model is that there is no way to simulate 100 players performing simultaneously on stage, nor to determine their reactions to the hall's sound.

Drawings of the TOC hall, as built, are shown in Fig. 4. The main floor is 32.2 m long and 20 m wide. The sections show the distorted pyramidal shape of the ceiling. In the 10:1 tests, five ceiling configurations were evaluated: case 1 was with smooth ceiling surfaces; case 2 with uniform steps, and case 3 with uniform steps and a stage house like that in Boston Symphony Hall. Case 4 was with non-uniform steps, and case 5 with nonuniform steps and a canopy over the stage. Case 2 with uniform steps and diffusing blocks and a canopy over the stage was selected for architectural and acoustical reasons.

Throughout the acoustical tests four positions of the sound source on the stage were used, designated S_0, S_L, S_R, and S_H, shown in Fig. 5. Because the hall is symmetrical, eight receiving positions were selected on the main floor and four or five positions in the balconies. Position 102 on the main floor is of particular interest because it is both off center and is an important audience position.

In Fig. 6, photographs of the interior of a late version of the 10:1 wooden model and of the dodecahedral sound source are shown. Movable throughout the ''audience'' areas were (1) $\frac{1}{8}$-in. electret microphones for monaural measurements and (2) ''dummy'' heads, each about 2 cm in diameter fitted with two tiny microphones at the ear positions, for binaural measurements. The numbering of the audience positions is also shown in Fig. 5. In Fig. 7, reflectograms from the computer model and the 10:1 model are shown for comparison. The sound source was at S_0. In the upper half of Fig. 7, the ''listener'' was at main-floor position 102 and in the lower half at first balcony position 23. Early reflections are very important, both as to time of arrival, amplitude, and direction. It is apparent that position 102 was superior to position 23 at that stage of the development, because there are 13 reflections in the first 80 ms, while at position 23 there are only 6, and the levels of the first 5 reflections at position

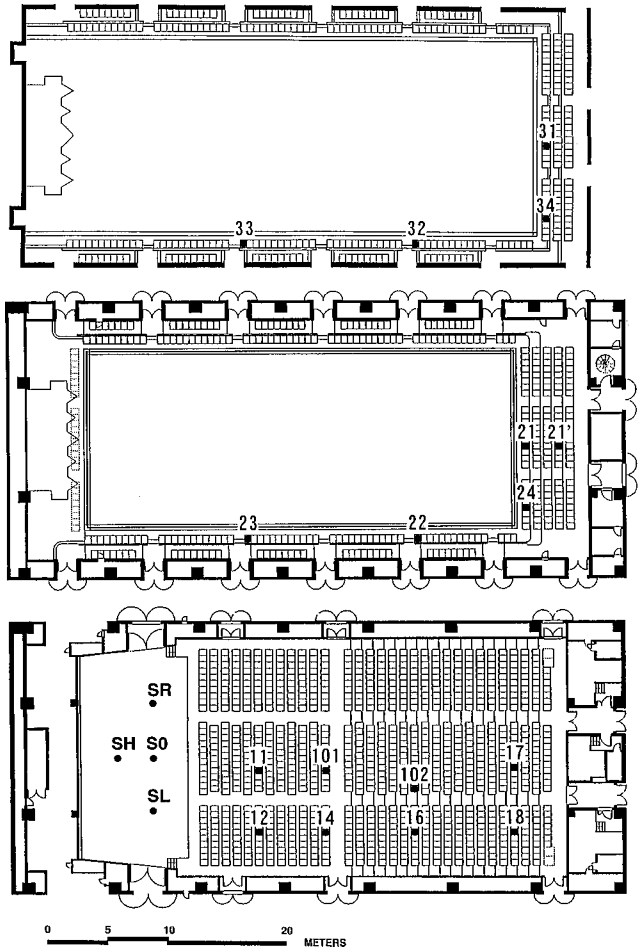

FIG. 5. Stage and audience measuring positions used by Takenaka Research and Development Institute for symmetrical models and halls. (Lower) Four positions of omnidirectional sound source on stage, with S_0 being referred to most often in this paper, and eight audience measuring positions on main floor, with Nos. 101 and 102 being referred to most often. (Middle) Five audience positions in first balcony with Nos. 21 and 23 being referred to most often. (Upper) Four audience measuring positions in second balcony, with No. 32 being referred to most often.

23 are well below those at 102. By adjusting the slopes of the balcony faces, adding large scale diffusion to them, and adjusting the angle of the lighting trough at the upper edge of the rectangular portion, the sound at position 23 was later improved. The discrete reflections shown in the lower halves were spread out when diffusion was added, as will be shown later in the reflectograms for the finished hall. The tests in the models assured that the rectangular/pyramidal shape of the hall desired by the architect would yield values of intimacy, loudness, spaciousness, and clarity that would be near ideal. Attention was then focused on reverberation time, bass ratio, hanging reflector, and sound diffusion on ceiling and side wall surfaces.

Determination of reverberation times in the 10:1 model was more difficult than expected because no satisfactory method was then available for simulating the audience. This difficulty was improved on after we learned the effectiveness of the cloth covering that is described in Sec. VI below. In Fig. 8, the sound pressure distributions at mid-frequencies on the main floor and the balconies, using pink noise in eight octave bands, are shown in comparison with the level at

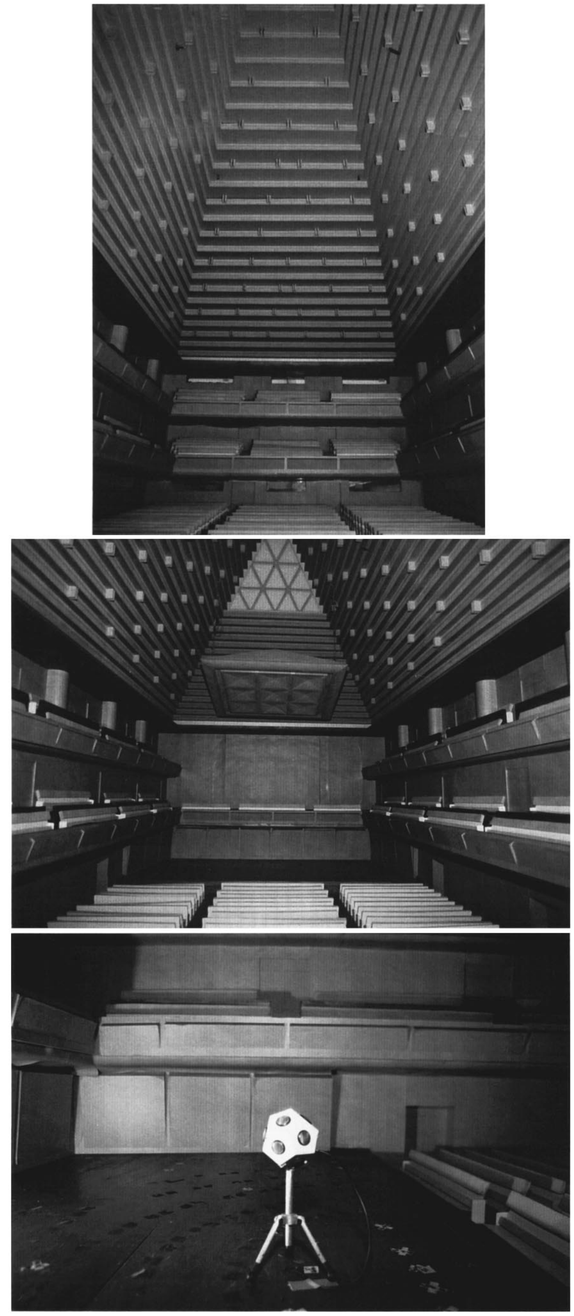

FIG. 6. Photographs of 10:1 wooden model, taken at late stage of the TOC design project.

position 101 in the center of the hall. No long-path echoes were discovered on-stage or in the audience either by listening or by measurement.

By the Fall of 1992, the results of acoustical tests of the various architectural features that had been installed in the models were reported to the architect. Because the ceiling of TOC is shaped like a pyramid, the architect wanted the overstage reflector to be pyramidal with its dimensions as small as possible consistent with accomplishing the necessary acoustical results. He also requested that the space at the front of the hall, above the first balcony, must be tall enough to accommodate the organ pipes, which appeared to be in conflict with the lower height needed to achieve the desired reverberation time.

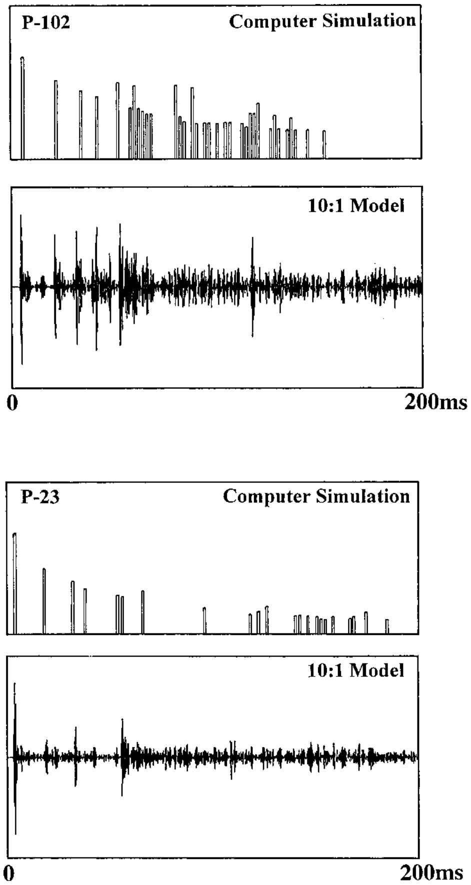

FIG. 7. Comparison of computer CAD model and 10:1 model reflectograms for 2000 Hz at positions 102 and 23, with omnidirectional source at S_0 on stage. These charts are from an early stage of the design project.

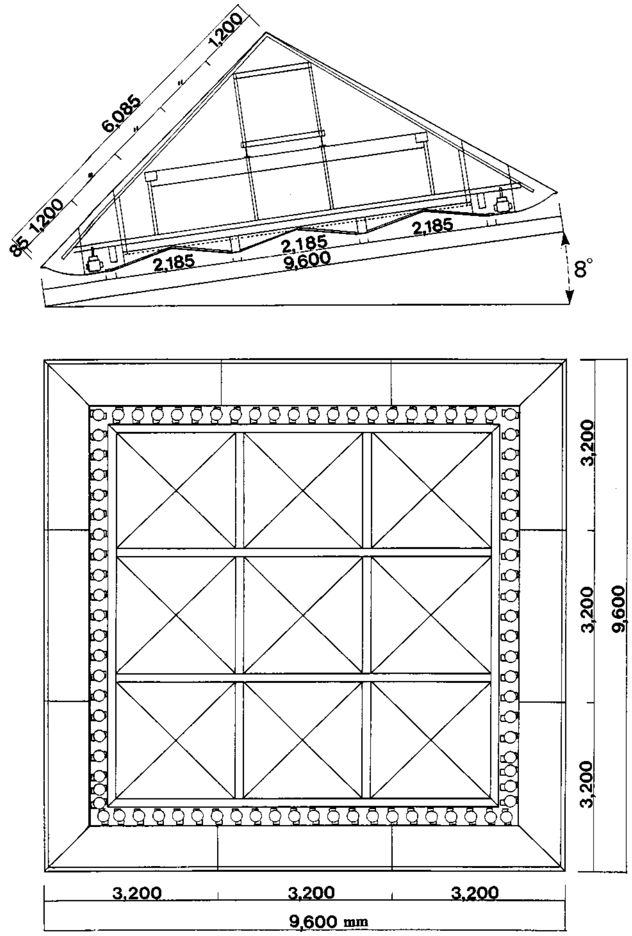

FIG. 9. Outline drawing of the pyramidal sound reflector hung above stage in TOC concert hall. The nine sections act to diffuse the sound so that performers on the stage can hear themselves and other players. The reflector also strengthens the early sound in the front rows of the audience. The dimensions are in millimeters.

The consultants concluded that the interior surfaces could be comprised of two layers of heavy wood with an overall thickness of 25 mm.

At this point, attention was turned to the detailed designs of the over-stage reflector and the pyramidal ceiling which must produce the desired sound diffusion. A specific design for the chairs also followed so that samples could be fabricated and tested acoustically in a reverberation chamber. Other items that needed laboratory consideration were (1) the fine-scale sound-diffusing irregularities on the side walls beneath the first balcony; (2) the large-scale sound-diffusing irregularities for the balcony fronts, and (3) the final orientation of all reflecting surfaces.

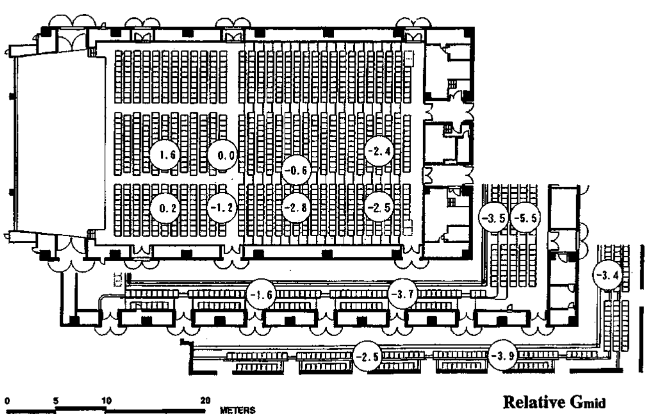

FIG. 8. Relative values of the strength factor G_M (average of 500- and 1000-Hz values) measured at 15 audience positions with an unidirectional source on stage at S_0. The reference position is No. 101.

V. LABORATORY DESIGNS, TESTS, AND RECOMMENDATIONS

In response to the above lists of needs, the following designs, tests, and recommendations were made by the acoustical consultants:

Reflecting canopy: Using the 10:1 model it was determined that (1) the lateral dimensions of the lower surface of the canopy should be no smaller than about 10 m on a side, (2) its slope, that is to say, its angle relative to horizontal, should be about 8 degrees; (3) the detailed shaping of the lower surface must be irregular, preferably with both large- and small-scale irregularities so as to diffuse the reflected sound, thus making the balance better among the sections of the orchestra as heard on stage and in the audience; and (4) the outer 0.5 m around the reflecting surface should preferably be curved up to increase the canopy's reach. The final design of the reflecting surface is shown in Fig. 9.

Organ pipe space: The consultants insisted that the height of the ceiling must be chosen to produce the desired

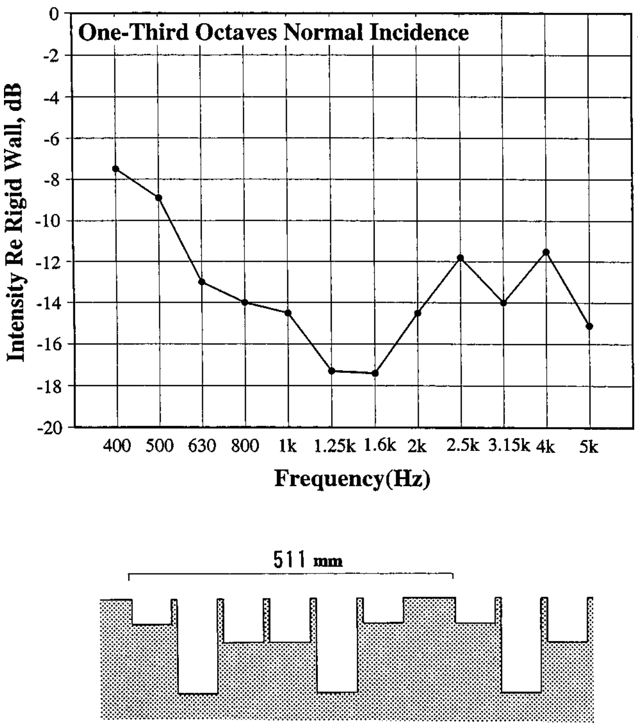

FIG. 10. (Lower) Design of Schroeder QRD sound diffusers installed horizontally on the rear wall of the pyramid facing the stage. (Upper) Reflected intensity measured in one-third-octave bands at normal incidence. The sound reflected back to the stage is reduced by more than 12 dB in the frequency bands from 630 to 5000 Hz. The QRD directs a considerable part of the diffused sound energy to the side walls of the pyramid which, on reflection, strengthens early lateral reflections.

reverberation time. Because only the lowest-frequency pipes need be long, it was urged that the organ builder bend them to fit the necessary space.

Pyramidal ceiling details: To preserve the aesthetic feel of the room, the architect demanded that the steps in the ceiling be uniform. To permit this, it was recommended that the long pyramidal surface be covered with Schroeder quadratic residue diffusers (QRD) and that sound-reflecting blocks be placed at intervals of 4.5 m on alternate steps along the lengths of the other three surfaces. As designed, the QRDs (Fig. 10, lower) scatter the sound laterally, thus the scattered sound strikes the side surfaces of the ceiling where they are further diffused laterally by the steps and the reflecting blocks. Laboratory tests showed that there would be no coloration owing to the steps. Sound directly striking the sides of the ceiling is also diffused by this combination. A further advantage of the QRDs is that they reduce the level of sound that is reflected directly back to the stage, thus eliminating what might have been a weak, but disturbing, on-stage echo (Fig. 10, upper).

Selection of chairs: The basis for the selection of the chairs turned out to be a sizable research project. The results are given in Beranek and Hidaka (1998). The design selected is similar to the chairs in the Grosser Musikvereinssaal of Vienna and is shown in Fig. 11. The seat cushion is about 5 cm thick, and 60% of the front of the seat back is a 2-cm-thick cushion.

Fine-scale diffusion on lower side and rear walls: It had been learned from listening tests in New York's Philharmonic Hall that sound reflected from smooth surfaces gave a peculiar ''acoustical glare'' to the music which could be eliminated by reducing the amount of sound reflected at the high frequencies (above 1000 Hz). The laboratory program developed several fine-scale irregularities for the lower side walls that scattered the high-frequency sound on reflection, thus giving the sound an ''acoustical patina.'' The detailed design acceptable to the architect is shown in Fig. 12.

Large-scale diffusion on balcony fronts: The model tests showed that for producing the best reflectograms at all parts of the audience, the balcony fronts would need to be sloped forward as shown in Fig. 13. Large-scale diffusion was created by the steps and the bottom edges were rounded to reflect the high frequencies more uniformly over the audience areas. In addition, vertical interruptions (protruding wooden blocks) are placed along the lengths of the balcony fronts on alternate steps, about 1.8 m apart (see Fig. 4).

All of the above changes were incorporated into the 10:1 scale model and RTs, reflectograms and C_{80}'s at 15 audience positions, as well as ST1 and reflectograms for various source positions on stage were determined. The improvement in the sound for 2000 Hz at seat 23 can be seen from Fig. 14 by comparison with the reflectogram for the 10:1

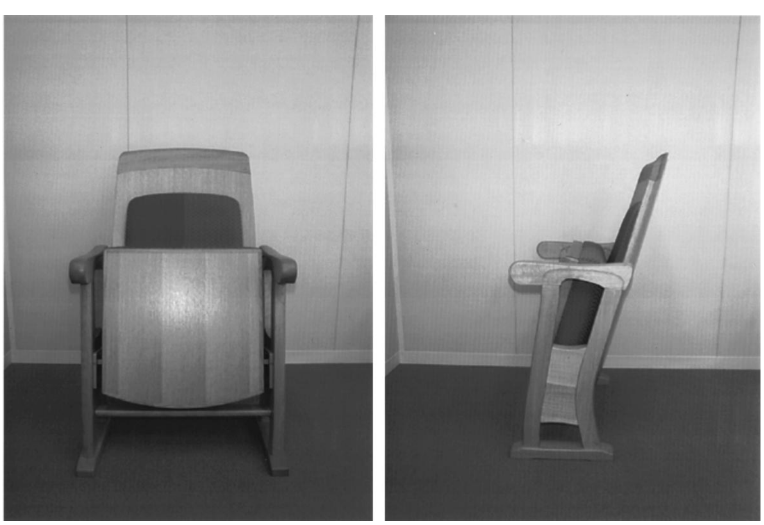

FIG. 11. Photographs of the audience seats. These are similar to those in the Vienna, Grosser Musikvereinssaal.

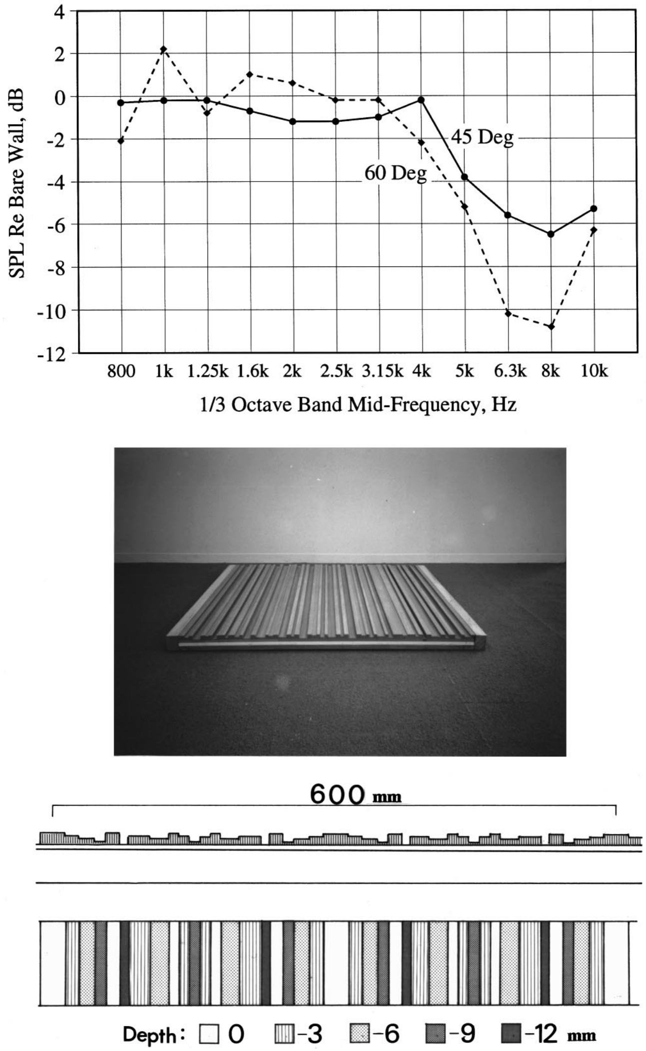

FIG. 12. Fine-scale diffusing surfaces on the side and rear walls of the rectangular portion of the TOC concert hall. (Lowest) Depth in millimeters of the grooves. (Next up) Section view of the pattern of the grooving. (Middle) Photograph of the diffusing panel as tested in the laboratory. When installed on the sidewalls the grooves are vertical. (Upper) The sound pressure level relative to that from a hard flat surface, with the sound wave incident at 45 and 60 degrees. The microphone was located at the optical reflection angle.

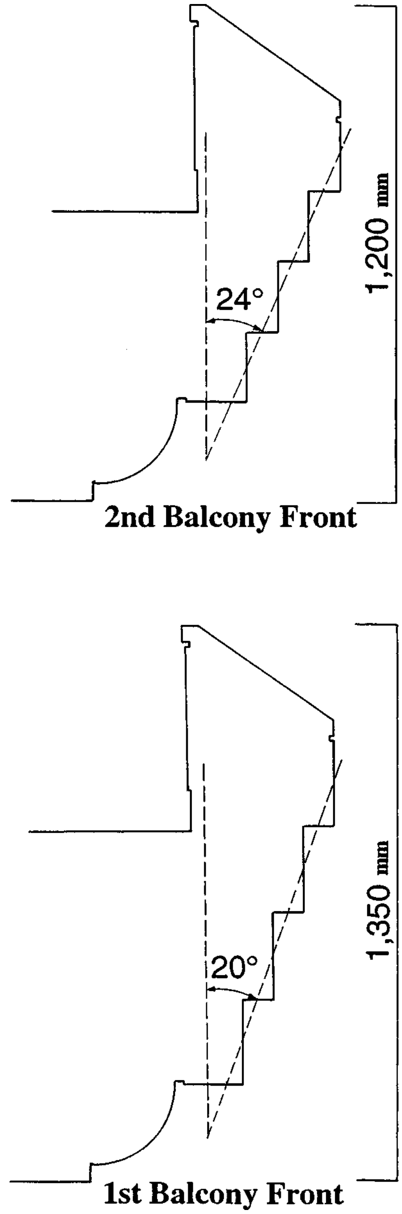

FIG. 13. Design of the balcony fronts. The angles of the facia were set to produce the most uniform sound reflectograms among the audience seats. The curved lower edge is to spread the early sound at high frequencies more uniformly over the main floor seating areas.

model of Fig. 7. Although there was some variation in the reflectograms in different parts of the TOC hall, the uniformity achieved seemed excellent and the architect proceeded with the final drawings in early 1993.

VI. THE HALL AS BUILT

The hall as finally constructed is shown by the photographs in Fig. 15. Construction was completed in late fall of 1996, nearly a year ahead of its opening! Reverberation times were measured before installation of the seats on June 8, 1996 and the RTs and residual absorption coefficients are given in Table II. After installation of the seats, the RTs were again measured and the absorption of the seats determined. The results are shown in Table III along with absorption coefficients measured in the reverberation chamber using the ISO procedures. The large difference between the two measurements of the two absorption coefficients are due in part to the difference in the sound fields, but more because the upholstery of the chairs as installed differed from that of the sample chairs tested in the reverberation chamber. Apparently, the cloth covering was back-sprayed, thus reducing its

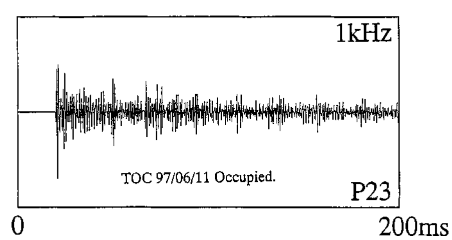

FIG. 14. Measured reflectogram in the completed hall for 2000 Hz at position 23.

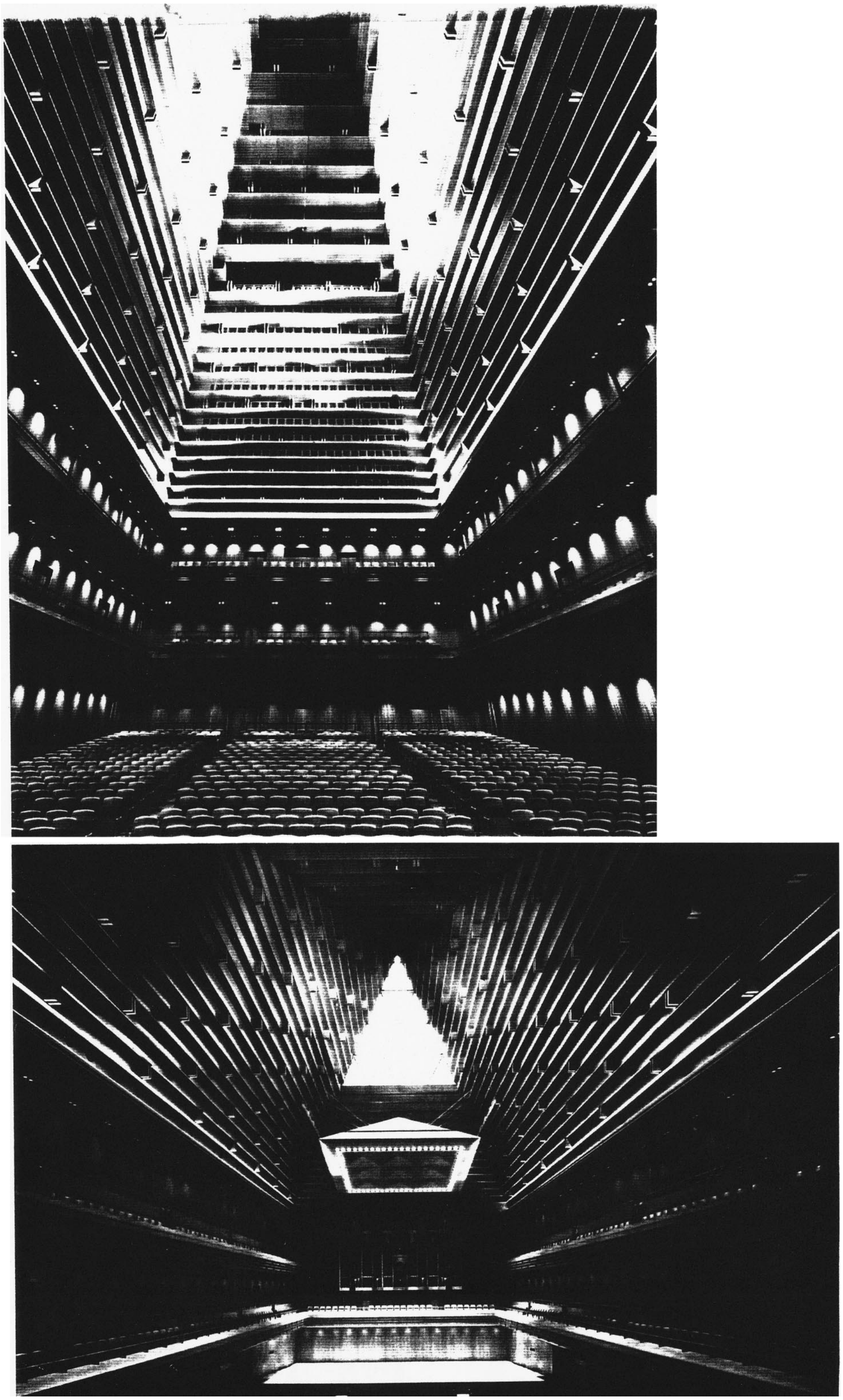

FIG. 15. The TOC concert hall. (Upper) View of hall from stage. Irregular balcony fronts and sides of pyramidal ceiling create diffusion of the sound field. The long rear side of the pyramid is fully covered with Schroeder quadratic residue diffusers QRD to diffuse a large portion of the sound laterally and to reduce the intensity of the sound returned to the stage. (Lower) View of the hall from the first balcony center. The 9.6-m square pyramidal canopy hangs over the stage. With its irregular undersurface and hanging at an angle of 8 degrees, sound from all instruments is reflected uniformly to the front half of the audience on the main floor and the sound of every musician is reflected to every other musician. The wooden interior and the pipe organ add to the beauty of the hall. **Architect**: Takahiko Yanagisawa. **Photos**: Studio Murai, Tokyo.

porosity. A rehearsal curtain, hung from the ceiling about a $\frac{1}{3}$ of the way back in the main floor seating, is available.

In a separate paper it is shown that a simple means can be used to simulate the occupied condition of a concert hall so that the objective acoustical parameters can be measured at will without involving real people (Hidaka *et al.*, 1998). The means consists of laying a sheet of cloth (flow resistance between 630 and 870 Pa*s/m, and thickness about 0.5 mm) over the seats. Measurements of RT in the NNT opera house for (people) occupied and simulated (cloth cover) occupied conditions are shown in Table IV. This discovery meant that many days of tests could be scheduled in the hall with equivalent ''full occupancy.''

Reverberation measurements were made in the TOC concert hall after laying the cloth covering over all seats, but before installation of the pipe organ. The measured RT was

FIG. 15. (*Continued.*)

greater than expected, making it seem desirable to add a sound-absorbing blanket above the lighting cove at the top of the rectangular section [see Fig. 4(d)]. This was done. In the next few months, the pipe organ was installed. The RTs measured preceding the tuning concert, with cloth covering, are shown by the uppermost curve in Fig. 16.

VII. TUNING CONCERT

The tuning concert was held 11 June 1997. Seiji Ozawa conducted the New Japan Philharmonic Orchestra. Three compositions were performed: Brahms, *Symphony #3*; Tchaikovsky, *Piano Concerto, #1 B-Flat-Minor*; and Brahms, *Alto Rhapsody, Op. 53*. At the rehearsal in the afternoon, with the cloth covering over the seats to simulate the audience, the sound was excellent. At the tuning concert that evening with a real audience, the sound was unexpectedly different, at least to some observers at some seats and to some orchestra members. The reverberation time with real audience is shown as the lowest curve in Fig. 16, a greater difference from the uppermost curve than shown in (A) and

TABLE II. (A) Reverberation times and (B) residual sound absorption coefficients for the TOC hall measured before installation of seats. *Residual* means average absorption coefficients for all surfaces, except those that would be covered by audience and orchestra seating, but including absorption by chandeliers, ventilation grilles, doors, etc.

	Frequency (Hz)					
	125	250	500	1000	2000	4000
(A)	3.18	3.86	4.54	4.61	4.22	3.50
(B)	0.14	0.11	0.09	0.08	0.08	0.065

TABLE III. (A) Reverberation times and (B) sound absorption coefficients for the unoccupied seats in TOC hall measured after installation of seats. (C) Sound absorption coefficients for 20 TOC seats (5 seats×4 rows) measured in the reverberation chamber using ISO procedures.

	Frequency (Hz)					
	125	250	500	1000	2000	4000
(A)	2.23	2.62	2.86	2.98	3.12	2.92
(B)	0.41	0.37	0.37	0.33	0.25	0.19
(C)	0.27	0.40	0.52	0.47	0.40	0.34

TABLE IV. (A) Reverberation times measured in NNT opera house with actual audience. (B) Same, but with cloth covering over seats to simulate the audience.

	Frequency (Hz)					
	125	250	500	1000	2000	4000
(A)	1.62	1.59	1.49	1.49	1.42	1.32
(B)	1.59	1.56	1.46	1.48	1.40	1.22

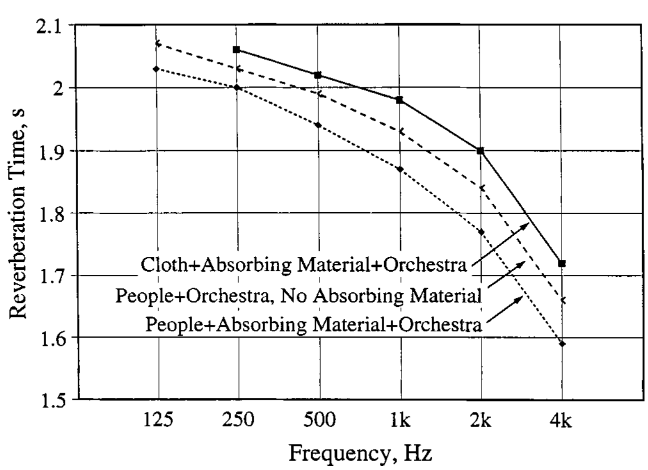

FIG. 16. Measured reverberation times after installation of the pipe organ: (Upper) Occupied hall simulated by cloth covering, with orchestra on-stage and with sound absorbing material in the lighting cove. (Middle) Occupied hall as finally configured, with real audience and orchestra on stage and without sound absorbing material. (Lower) Occupied hall, with real audience and orchestra and with sound absorbing material in the lighting cove.

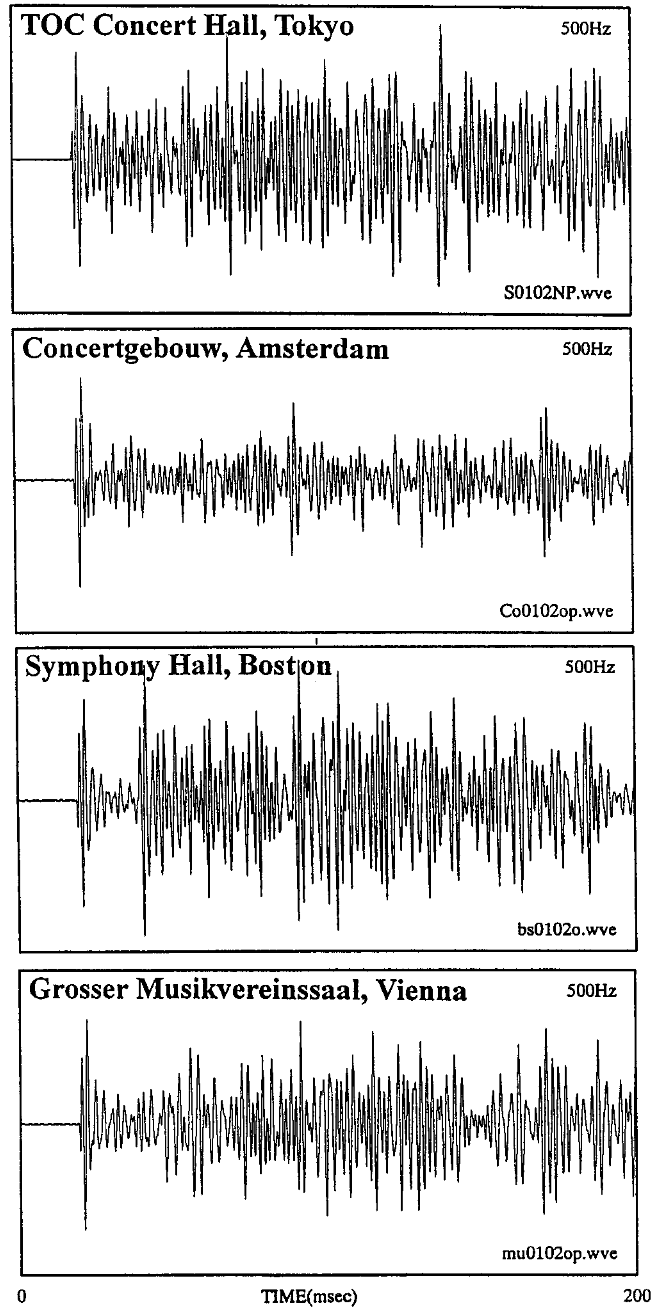

FIG. 17. Reflectograms for 500 Hz measured at seat 102 on main floor of four concert halls. The Amsterdam, Boston, and Vienna halls are rated subjectively by conductors and music critics as ''superior halls'' (Beranek, 1996, p. 58). The TOC reflectograms here and in the next two figures resemble those of Boston most closely.

(B) of Table IV. Because the sound at the same seats with the cloth covering was judged to be better, it was decided to remove the added absorbing material in the lighting cove. The RTs with (people) audience and no absorbing material are shown by the middle curve of Fig. 16, measured opening night.

Reflectograms at position 102 (see Fig. 5, lower) at 500, 1000, and 2000 Hz are shown in Figs. 17–19 for TOC, Amsterdam, Boston, and Vienna concert halls, all measured with the same equipment and by the same personnel. All halls were unoccupied. The reflectograms for the TOC hall appear to be closest to those for Boston Symphony Hall.

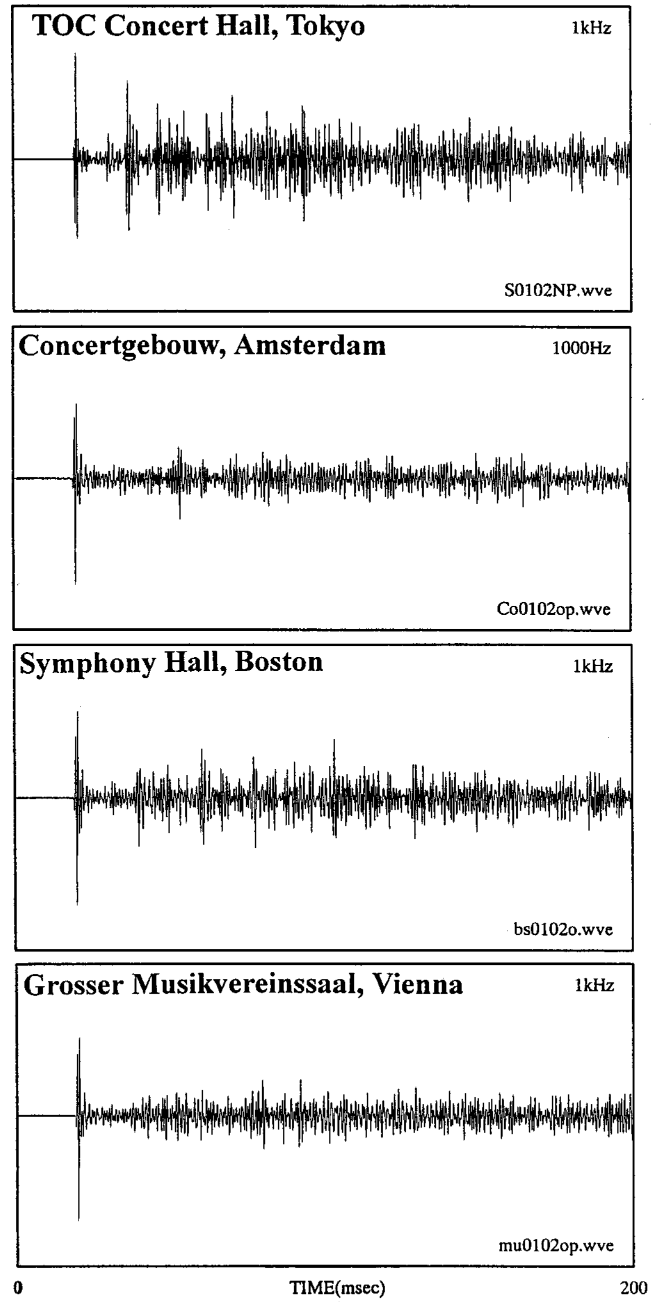

FIG. 18. Same as Fig. 17, except for 1000 Hz.

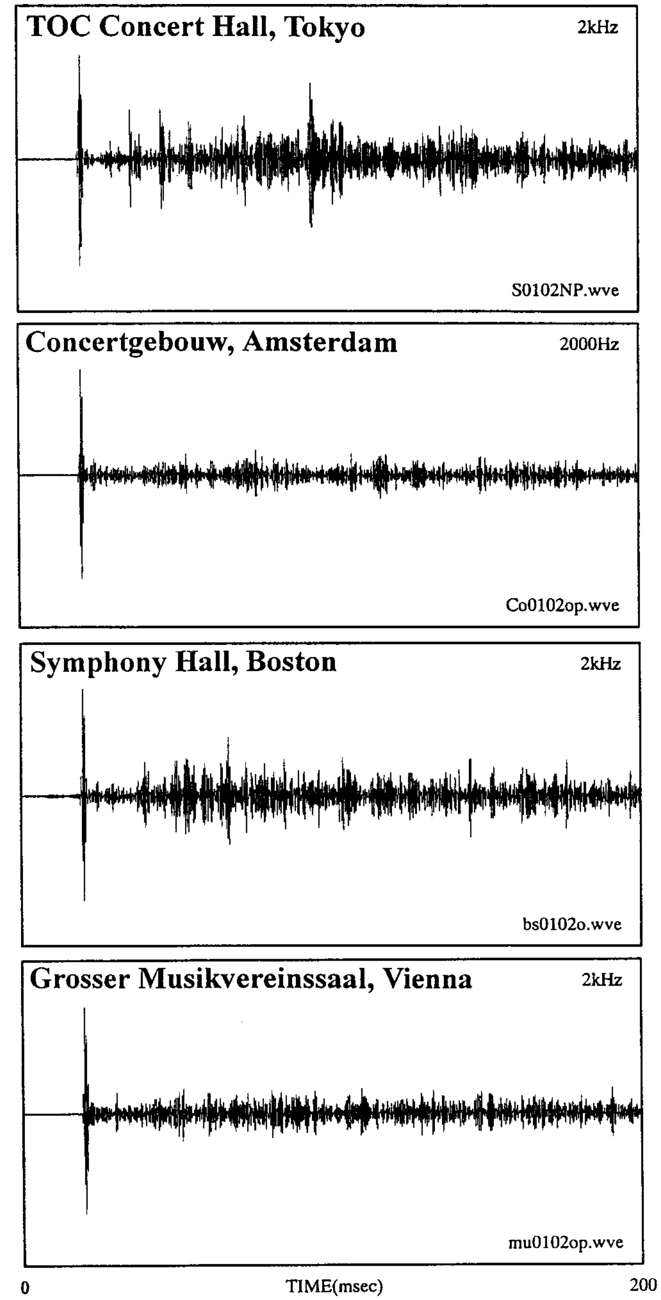

FIG. 19. Same as Fig. 17, except for 2000 Hz.

VIII. OPENING NIGHT, 10 SEPTEMBER 1997, AND PROFESSIONAL EVALUATION

The TOC Concert Hall opened 10 September 1997, with the Emperor and Empress of Japan in attendance. Seiji Ozawa conducted J. S. Bach's *B-Minor Mass* with the Saito Kinen Orchestra. The concert was excellent in every respect. The acoustics were successful. Concerts by visiting symphony orchestras, string ensembles, concertos for piano, violin and cello soon followed. The reviews by music critics were excellent. Letters were received from some of the performers and interviews were held with others. All praised the acoustics and there were no negatives. Excerpts from three letters are:

Yo Yo Ma, cello concerts, 30 September and 1 October: ''This hall simply has some of the best acoustics in which I have ever had the privilege to play...the pyramid-like structure and the unusual lighting gives...[the TOC Hall] a spiritual feel that I never experienced in any other hall... What has been accomplished is a miracle!''

Kent Nagano, Music Director, Opera National de Lyon, two ONL orchestral concerts, 27 and 28 September: ''From the perspective of having visited many concert halls throughout the world together, we found in this concert hall that rare combination of esthetic, emotion, spirit and acoustical balance that conspire to make a concert hall great...the architectural vision and the marvelously excellent acoustics seem to at once provoke imagination, generate a warmth of intimacy, while providing a sense of quiet timelessness, mystery and awe.''

TABLE V. Measured acoustical parameters for Tokyo Opera City concert hall, opened 10 September 1997 (1632 seats).

	Frequency (Hz)					
	125	250	500	1000	2000	4000
RT, unoccupied	2.16	2.51	2.72	2.88	2.98	2.72
RT, occupied	2.07	2.03	1.99	1.93	1.84	1.66
EDT, unoccupied	2.03	2.24	2.65	2.73	2.84	2.54
EDT, occupied	1.76	1.77	1.84	1.81	1.73	1.51
$IACC_A$, unoccupied	0.89	0.68	0.18	0.12	0.11	0.12
$IACC_A$, occupied	0.86	0.66	0.26	0.19	0.17	0.21
$IACC_E$, unoccupied	0.92	0.75	0.36	0.25	0.22	0.25
$IACC_E$, occupied	0.88	0.66	0.33	0.29	0.26	0.31
$IACC_L$, unoccupied	0.88	0.66	0.15	0.09	0.07	0.05
$IACC_L$, occupied	0.85	0.69	0.23	0.13	0.08	0.06
$C_{80}(3)$, dB, unoccupied	−2.0	−3.5	−2.9	−2.7	−2.6	−2.2
$C_{80}(3)$, dB, occupied	−2.5	−1.6	−0.8	0.2	0.7	1.8
G, dB, unoccupied	4.0	5.4	6.0	6.3	6.9	6.3
G, dB, occupied	3.5	4.2	4.7	4.5	4.6	3.9

András Schiff, Schubert Piano Sonatas, 24 and 27 November: ''This is a wonderful auditorium, an architectural masterpiece...The sound is warm, round, and reverberant, when the audience is present this is just ideal. It's like a beautiful cathedral without the echo...the feeling of intimacy—so important in music—is achieved.''

An interesting thread throughout these three letters (and letters and interviews of others) relates to the overall impression that the hall makes on listeners and performers. Many of the letters and interviews used words like, ''mystery and awe,'' ''spiritual feel,'' ''intimacy,'' and ''like an Aztec pyramid.'' These words signify, at least to the authors, that a successful collaboration between the architect and the acoustical consultants took place.

IX. MEASURED ACOUSTICAL PARAMETERS

The measured acoustical parameters for the TOC Concert Hall are given in Table V. The occupied conditions for IACC were measured at the test concert with eight dummy heads on the main floor and nine in the balconies, each head fitted with binaural microphones. The other occupied parameters were measured at the same positions with omnidirectional microphones. The values are the averages of the numbers at the 17 positions. All unoccupied data were taken at all positions shown in Fig. 5 and averaged. Comparisons between these data (given first) and the ranges of the data measured in the Vienna Musikvereinssaal, Amsterdam Concertgebouw, and Boston Symphony Hall (given in parentheses) are as follows. (The values for RT and BR are for full occupancy and the other parameters are for the halls unoccupied, because those are the only data available): $RT_{MID}=1.96$ s (three-hall range 1.9–2.0 s); $EDT_{MID}=2.69$ s (range 2.4–3.0 s); ITDG=15 ms (range 12–21 ms); $C_{80}(3)=-2.7$ dB (range -3.7 to -2.7 dB); $[1-IACC_{E3}]=0.72$ (range 0.62–0.71); BR=1.05 (range 1.03–1.11); $G_{mid}=6.2$ dB (range 5.4–7.8 dB); and $ST1=-12.1$ dB (range -17.8 to -13.7 dB). All data are for equivalent positions and were taken by the same measuring crews. By comparison with the three acknowledged world's best halls, the numbers indicate that TOC has optimum reverberation, clarity, intimacy, spaciousness, warmth, and strength of sound. The noise levels measured in the unoccupied hall with the HVAC in operation are shown in Fig. 20 which yield a rating of NCB-14.

X. CONCLUSION

As documented above, the subjective judgments and the measured data place the TOC concert hall in the category ''Excellent.'' This success with an entirely new architectural solution, the pyramidal ceiling, indicates that it is not necessary to duplicate previously successful halls precisely to achieve excellent results, provided the principal acoustical parameters for the audience areas listed in the previous para-

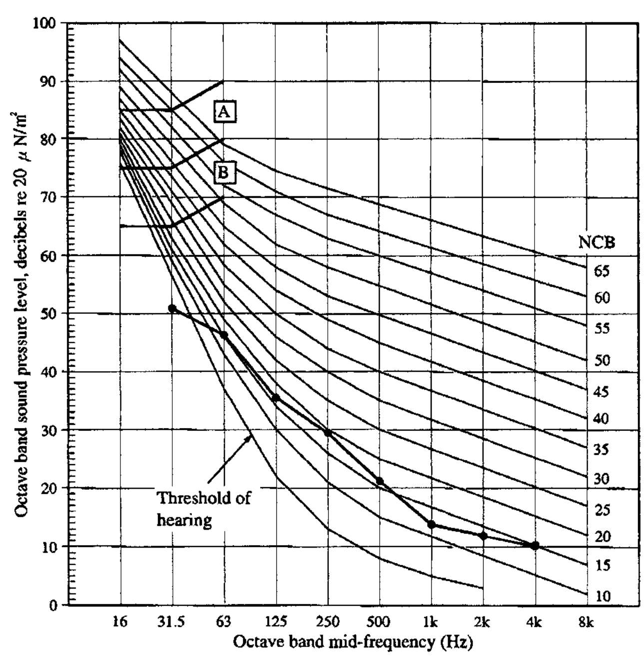

FIG. 20. Measured noise levels in unoccupied TOC Hall with HVAC systems in operation.

graph have values consistent with those for the best halls, and the stage acoustics are acceptable to the musicians.

ACKNOWLEDGMENTS

We wish to express our deep appreciation for the excellent cooperation and relationship with architect Takahiko Yanagisawa and his project managers, Paul Baxter and Hiroshi Wada. Thanks are owed the administrations of the concert halls in which acoustical measurements were made.

APPENDIX: EQUATIONS FOR ACOUSTICAL PARAMETERS

Interaural cross-correlation coefficient, $\mathbf{IACC_{E3}}$: This quantity is a measure of the difference in the sound pressures $p(t)$ at the two ears,

$$\mathrm{IACC}_{E3}=\left|\frac{\int_0^{0.08}p_L(t)p_R(t+\tau)\,dt}{(\int_0^{0.08}p_L^2(t)\,dt\int_0^{0.08}p_R^2(t)\,dt)^{1/2}}\right|_{\substack{\text{MAX \&}\\ \text{3-BAND}}}$$

$$\text{for}\quad -1<\tau<+1,$$

where L and R designate the entrances to the left and right ears, respectively, and the measurement is usually made with a standard dummy head or with tiny microphones at the ears of a person with head dimensions approximating that of the standard. Time ''0'' is the time of arrival of the direct sound from the impulse radiated by the source on the stage or in the pit. The function is determined for values of τ between -1 and $+1$ and the magnitude of the maximum value so obtained is used. Because of the short range for τ, the function is meaningful in room acoustics for measurements in octave bands of 500 Hz and above. The letter ''E'' stands for ''early sound,'' i.e., the sound that arrives within the first 80 ms after the direct sound and ''3'' stands for averaging the measured quantity in the three octave bands, 500, 1000, and 2000 Hz.

As a measure of spaciousness IACC_{E3} eliminates sound waves arriving from the direction of the source and measures the difference in the waves arriving at the two ears, making it a binaural measurement, and at frequencies critical to the fast moving tones of string instruments. It takes into account both phase and amplitude in this difference and has been shown by Beranek (1996), Hidaka *et al.* (1995), and Okano *et al.* (1998) to be superior to lateral fraction LF_{E4}. Lateral fraction is a monaural measurement which only measures the magnitude of sound pressure arriving at directions other than directly ahead weighted by $\cos^2\theta$, where $\theta=90$ degrees is in the direction of the source. It considers the sound pressures mainly at low frequencies, and it does not correlate as well as IACC_{E3} with subjective judgments of acoustical quality of concert halls as rated by conductors, music critics, and qualified symphonic listeners.

Strength factor, G: This quantity, expressed in decibels, is a measure of the sound pressure level at a point in a hall, $p(t)$, with an omni-directional source on stage, minus the SPL that would be measured at a distance of 10 m from the same sound source operating at the same power level and located in an anechoic chamber $p_A(t)$,

$$\mathrm{G}=10\ \log\frac{\int_0^3 p^2(t)\,dt}{\int_0^3 p_A^2(t)\,dt}\ \mathrm{dB},$$

where $p_A(t)$ is the free-field sound pressure level at a distance of 10 m. $\mathrm{G}_{\mathrm{mid}}$ means average of the measured values for the 500- and 1000-Hz octave bands.

Bass ratio, BR: This quantity is the ratio of the low- to mid-frequency reverberation times for halls fully occupied,

$$\mathrm{BR}=\frac{\mathrm{RT}_{125}+\mathrm{RT}_{250}}{\mathrm{RT}_{500}+\mathrm{RT}_{1000}},$$

where the RTs are the reverberation times at the frequencies shown in the subscripts measured in halls fully occupied.

Clarity factor, $\mathbf{C_{80}}$: This quantity, expressed in decibels, is the ratio of the early sound energy (0 to 80 ms) to the late (reverberant) sound energy (80 to 3000 ms),

$$\mathrm{C}_{80}=10\ \log\frac{\int_0^{0.08}p^2(t)\,dt}{\int_{0.08}^3 p^2(t)\,dt}\ \mathrm{dB}.$$

$\mathrm{C}_{80}(3)$ means the average of the clarity factor over the three octave bands, 500, 1000, and 2000 Hz.

RT and EDT: RT is the reverberation time in seconds measured starting after the decay has progressed -5 dB and until it reaches -35 dB, the result multiplied by 2. When measurements are made from stop chords recorded during performances, Schroeder's integration method must be used to detect unusable decay curves. EDT is the reverberation time obtained during the first 10 dB of sound decay. It generally is not measured from stop chords because uniform decay curves are generally not obtained in the first few decibels of sound decay.

Support factor, ST1: The support factor ST1 is the difference in decibels between two measurements of sound pressure level on a stage where the orchestra members play. The nondirectional sound source emits an impulse and the microphone receives it at a point 1 m removed from the center of the source. The first measurement is of the energy in the time interval from 0 to 10 ms and the second measurement is from 20 to 100 ms. Nearby music stands and chairs are moved to prevent their influencing the measurement.

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