Acoustical Design of the Tokyo Opera City (TOC) Concert Hall, Japan
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Abstract: The TOC concert hall seats 1636, volume 15,300 m³, and reverberation time, with audience and orchestra, 1.95 s.
Measurements on CAD computer and 1:10 wooden models 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 nearer the stage than the rear of the hall and 28 m above the main floor. This unique shape was analyzed on the models so that all interior surfaces combine to distribute sources on stage uniformly over the seating areas and to yield optimum values for RT, EDT, BR, ITDG, diffusion and loudness (for definitions see Beranek 1996, Concert and Opera Halls: How They Sound, Acous. Soc. Amer.) On the long ceiling facing the stage, Schroeder QRD diffusers provide diffusion, eliminate a possible echo, and strengthen lateral reflections. Performers judge the acoustics excellent.

INTRODUCTION
The TOC Concert Hall (TOC) is contiguous to the New National Theatre complex. A joint-venture design team was assembled by an Executive Committee, with Takahiko Yanagisawa of TAK Associated Architects as lead architect. The requirements presented to the acoustical consultants were: (1) approximately 1630 seats; (2) rectangular shape in plan; (3) primarily for concerts and recital performances; (4) reverberation time in the range of 1.8 to 2.0 seconds with full occupancy; (5) pyramidal ceiling; and (6) natural wood interior. Acoustics before April 1991 was the responsibility of S. Masuda.

On receiving the commission of Acoustical Design Consultant for the TOC in April 1991, L. Beranek met to lay out the program with the acoustical staff of the Takenaka R. & D. Institute of Chiba, Japan, headed by T. Hidaka, which was retained to make models and perform acoustical measurements. Beranek continued a systematic effort to assemble drawings, photographs, details on materials and acoustical data measured by world-wide acoustical engineers for sixty-six concert halls in regular use in twenty-two countries. The technical literature was reviewed to assist in establishing the important acoustical characteristics that should be determined at various stages of its design and after its completion. The results of these studies, including drawings, photographs, descriptions, and acoustical data are combined in Beranek (1996).

Hidaka and staff made measurements of the important acoustical parameters, including those recently developed, in nineteen concert halls. The next step was their design of a CAD computer model. This was followed by construction of a 10:1 wooden model in which the audience was simulated, and where impulse signals were radiated from a tiny loudspeaker at various positions on the stage to spherical heads in the audience with 1/8-in. microphones as "ears".

DESIGN AND MEASUREMENTS
The acoustical characteristics that appeared from the studies to be most meaningful, which were measured in existing halls, in models and in the completed hall, and the designs employed in TOC to accomplish them were:

A. Reflected sound waves from the surfaces of the hall including, direction and magnitude: The goal was to achieve uniform sound projection over the audience from all points on the stage. Because early sound yields musical clarity, the CAD model was used to determine the direction of the early waves arriving at each position and the 10:1 model was employed to furnish information on the sequence of wave arrivals and their strengths by use of sound-pressure/time plots called "reflectograms". The unique pyramidal ceiling and other features of the hall are shown in Figs. 1 and 2. The stage area is 10% greater than that in Boston Symphony Hall. Its sides are flared to better project the sound to the audience. The first balcony overhangs the back of the stage and is shaped to enhance communication among orchestral sections and the conductor. A flat, irregular surfaced canopy, 9.6 m square is hung over the front part of the stage. The architect's handling of the unique pyramidal concept and hung canopy is shown in Fig. 2. To enhance the energy in lateral reflections, and to avoid echoes as heard by musicians on stage, the long pyramidal surface facing the stage is covered by Schroeder QRD diffusers.

B. Reverberation time (RT) occupied, and early decay time (EDT) unoccupied: These quantities both affect the clarity and add fullness of tone (liveliness) to the music. They were measured both in the 10:1 model and in the concert hall at various stages of its completion. The RT goal at mid-frequencies was 1.9 to 2.0 seconds.

C. Bass strength (BR), the support that the hall (occupied) gives to the low notes of music in relation to the higher notes: We chose as a measure of BR the ratio of the sum of the RT's at 125 and 250 Hz to the sum at 500 and 1000 Hz. Achieving a ratio greater than unity was particularly difficult in TOC because of the architect's requirement that the interior surfaces of the hall be wooden. A satisfactory ratio was achieved by employing chairs that were lightly upholstered, modeled after those in Vienna's Grosser Musikvereinsaal.

D. Intimacy, the initial-time-delay gap t₁: The hall should return the first sound reflection to the center part of the main floor within 20 ms after arrival of the direct sound. The t₁ was obtained from impulse responses and drawings.

E. Spaciousness, measured by the quantity one minus the interaural-cross-correlation coefficient, (Hidaka, Beranek and Okano, 1995). A large value of spaciousness means that a considerable portion of the sound energy at listeners' ears arrives from near-lateral directions. Reflections from the parallel sidewalls, shaping of the balcony...
faces, scattering elements on the balcony faces and the QRD diffusers resulted in high values of \([1 - \text{IACC}_m]\).

F. **Diffusion**: Irregularities on the walls, balcony faces and ceiling give the sound a rich acoustical patina. The fine-scale diffusion on the side walls was carefully developed from laboratory measurements to be effective above 1 kHz.

G. **Clarity, \(C_m\)**, the ratio of the early energy (0 to 80 ms) to the reverberant energy (80 to 3000 ms) in dB.

H. **Quiet**: The HVAC noise, hall unoccupied, is about NCB-20. There are no troublesome echoes.

I. **Loudness**: The measure of loudness used is \((V/EDT) \times 10^2\) (Beranek 1996a).

TOC concert hall was completed nearly a year in advance of its opening, September 10, 1997. This afforded the opportunity for measurements, separately, before and after installation of seats, pipe organ and full occupancy. In the form of cloth covering, a simulated audience was developed. An unique opportunity led to data that suggest a new variable in the acoustics of concert halls, namely, the need for balance of energy in lateral reflections in different frequency regions. This potential factor obviously needs testing under controlled conditions.

**CONCLUSIONS**

The values of the measured quantities in the TOC Concert Hall (given first) and the ranges of those measured in the Vienna Musikvereinssaal, Amsterdam Concertgebouw and Boston Symphony Hall, world standards (in parentheses), are:

- \(\text{RT}_{60} = 1.96\) s (1.8-2.0 s);
- \(\text{EDT}_{60} = 2.69\) s (2.4-3.0 s);
- \(t_e = 15\) ms (15-21 ms);
- \(\text{C}_m = -2.6\) dB (-3.7 to -2.7 dB);
- \([1 - \text{IACC}_m]\) = 0.71 (0.62-0.71);
- \(\text{BR} = 1.05\) (1.03-1.11);
- \((V/EDT) \times 10^2 = 6.4\) dB (5.4 to 7.8 dB);
- \(\text{STI} = -12.1\) dB (-17.8 to -13.7 dB).

These numbers indicate that the TOC has optimum reverberation, clarity, intimacy, spaciousness, warmth and strength of sound. The responses of music critics, musicians, and conductors have been excellent, indicating by their statements that the hall takes its place among the best in the world. This success with an entirely new architectural solution, the pyramidal ceiling, indicates that the need to duplicate precisely previously successful halls to achieve excellent results is no longer necessary, provided the principal acoustical parameters listed above have values consistent with those for the best halls.

**REFERENCES**
