2.3, 2.7 Received 4 March 1966

Acoustical Measurements in Philharmonic Hall (New York)

M. R. Schroeder, B. S. Atal, G. M. Sessler, and J. E. West

Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

The acoustics of Philharmonic Hall in New York were evaluated by a new method utilizing a digital computer. Measurements were made before, during, and after a four-phase alteration program of the Hall. The following quantities were studied: (1) reverberation times based on the earlier and later portions of the decay, (2) energies of the direct sound and of reflections from the suspended ceiling, (3) "early" energies (energies arriving within 50 msec of the direct sound) and "reverberant" energies (arriving after 50 msec), (4) directional distributions of the early energies, (5) ratios of early-to-reverberant energies, (6) intensities of reflections from the rear wall, and (7) the over-all ambient noise level of the Hall. Reverberation times in the octave band 500–1000 Hz, for the main floor, based on the earlier and later portions of the decay, were found to be 1.9 and 2.1 sec, respectively, for the Hall in its original state. In the present state of the Hall, the main floor has a reverberation time of approximately 1.8 sec for both early and later portions of the decay, thus indicating a more exponential decay process. The early and early-plus-reverberant energies on the main floor showed a deficiency at low frequencies before the alterations; now, they have a relatively flat spectrum. For an early state of the Hall, the directional distribution of the early energy was close to that expected for a diffuse sound field on the second terrace, but deficient in lateral reflections on the main floor. For the present state of the Hall, the directional distribution of the early energy is less dependent on position, but there are still relatively more lateral reflections on the second terrace than on the main floor in the midfrequency range (250–1000 Hz).

INTRODUCTION

In early 1963, the Acoustics Research Department of Bell Telephone Laboratories, Inc., was invited by the management of Lincoln Center for the Performing Arts in The City of New York to assist in an objective evaluation of the acoustics of Philharmonic Hall. The invitation was accepted as an opportunity to gain experiences with new methods of room acoustical testing, which were being developed in connection with Bell Laboratories work on conference telephony. The method employed uses a digital computer and its peripheral equipment to generate test signals, to evaluate the response of the Hall to these signals, and to plot the results.[1]

The objective of this paper is to present the experimental results obtained in Philharmonic Hall and to discuss their subjective significance.

The results are based on measurements taken in Philharmonic Hall from May 1963 to October 1965, encompassing the original state of the Hall after its opening in September 1962, and all acoustical changes made prior to the reopening of the Hall for the 1965–1966 season.

I. ALTERATIONS IN PHILHARMONIC HALL

As might be expected for a new concert hall, opinions concerning the acoustics of Philharmonic Hall varied widely. However, many listeners agreed that the Hall had (1) a poor low-frequency response, affecting the audibility of cellos and double basses, (2) a lack of subjectively felt reverberation, (3) echoes from the rear wall, (4) inadequate sound diffusion, and (5) poor hearing conditions for the musicians on the stage.

A committee of acoustical consultants[2] recommended the following alterations in the Hall: (1) rearrangement of the suspended acoustical reflectors (clouds), (2) reshaping of part of the side walls, (3) installation of a solid stage enclosure, and (4) installation of risers on the stage. While these alterations were recommended mainly to correct the low-frequency response, the stage enclosure was also expected to provide better mutual

[1] B. S. Atal, M. R. Schroeder, G. M. Sessler, and J. E. West "Evaluation of Acoustic Properties of Enclosures by Means of Digital Computers," J. Acoust. Soc. Am. 40, 428–433 (1966).

[2] The committee was headed by V. O. Knudsen. Other members of the committee were H. Keilholz, P. S. Veneklasen, and M. R. Schroeder. The last named was responsible for the objective evaluation of the acoustics of Philharmonic Hall whereas H. Keilholz designed the changes in Phases III and IV.

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms

audibility for the musicians and to improve the subjective "reverberance" and diffusion in the Hall. Other recommended alterations were (5) tilting of the balcony faces, (6) absorptive treatment of the rear walls, and (7) installation of scattering elements on the side walls. Alterations 5–7 were recommended to reduce echoes and increase sound diffusion.

These proposals were implemented during a four-phase alteration program. In Phase I (July 1963), the suspended acoustical reflectors were realigned and parts of the side walls were reshaped. In Phase II (August 1963), absorptive treatment of the rear walls and tilting of the balcony faces were performed; optional risers for the stage were also provided. In Phase III (September 1964), a wooden stage enclosure was installed, and the ceiling over the stage was reshaped. In Phase IV (August 1965), scattering elements were added to the side walls. Also, new and less-absorptive seats were installed on the main floor.

II. RESULTS OBTAINED IN PHILHARMONIC HALL

Acoustical measurements were performed according to the method described in Ref. 1. Tone bursts with a duration of 24 msec were selected. After filtering, the half-power width of the tone-burst envelope is 11.5 msec, which was considered to be sufficiently short to resolve the direct-sound component and major early reflections. The corresponding 3-dB bandwidth of 38 Hz assures adequate frequency resolution. Twenty-three tone bursts with center frequencies at 83.3, 125, 166.7, $\cdots$, 1000 Hz were used, since the major problems in the Hall occurred in this frequency range. The time function and the spectrum of the tone burst with center frequency at 500 Hz is shown in Ref. 1 (esp. Figs. 1 and 2). For presentation in this paper, the data from the 23 frequency bands were, in general, combined into four octave bands from 63 to 1000 Hz.

The measurement procedure is illustrated in Fig. 3 of Ref. 1. The test tape, consisting of tone bursts with different center frequencies, is played back in the enclosure under study using a special nearly omnidirectional sound source. The sound source consisted of five 10-in. loudspeakers mounted on five sides of a box with dimensions of $2\times2\times2$ cu ft.

The measurements in the Hall were performed in its original state and after Phases I–IV at 12 earlevel microphone positions.[3] Seven of these positions were equally spaced along the center aisle of the Hall (at rows B, J, R, Y, FF, NN, and immediately behind row SS). Of the remaining five positions, two were on the main floor (close to seat SS14 and at seat J124), and three on the top balcony (Second Terrace) (seats H3, AA221, and CC123). Space averages for five positions[3] on the main floor, for the three positions on the second balcony, and for all 12 locations were computed for all of the measured quantities. Results of these measurements are described in Secs. II-A through G. The energies discussed in Secs. II-C through E are relative to the same reference level.

TABLE I. Main-floor averages of T_{15} and T_{15-30}.

Reverberation time (main-floor average) 500–1000 Hz	Original Hall	Hall after Phase I	Hall after Phase II	Hall after Phase III	Hall after Phase IV
T_{15}(sec)	1.89	2.06	1.72	1.86	1.85
T_{15-30}(sec)	2.06	1.99	1.87	1.85	1.80

A. Reverberation Time

Two differently defined reverberation times were measured: namely, T_{15}, based on the decay over the first 15 dB, and T_{15-30}, based on the decay from -15 to -30 dB. All reverberation times were derived by fitting straight lines to the integrated, squared envelope of the tone bursts. Thus, the reverberation times are based on an ensemble average of noise decays.[4]

The reverberation times T_{15} and T_{15-30} in the mid-frequency range (500–1000 Hz), averaged over five positions[3] on the main floor, are shown in Table I. (The second decimals shown in this Table are not subjectively significant, but are reproduced to facilitate comparisons.)

The increase of T_{15} for the main floor average after Phase I can be explained by a decrease in the energy of early arriving reflections from the raised ceiling. Because of this decrease in early energy, the integrated squared tone burst has a slower initial decay.[5]

After Phase II, absorptive treatment of the rear walls resulted in the elimination of echoes arriving with delays between 100 to 300 msec after the direct sound for the center portion of the main floor. Since these echoes cause a slow decay in the initial portion of the *integrated* squared tone burst,[5] their removal is expected to decrease T_{15} as observed. The increase of T_{15} after Phase III is probably due to the better sound diffusion resulting from the new stage. The greater diffusion is also reflected in the near equality of T_{15} and T_{15-30}.

The final reverberation time T_{15-30} decreased somewhat after each modification of the Hall. The absorptive treatment of the rear walls in Phase II, for example, decreased T_{15-30} by 0.1 sec. This decrease corresponds to that computed with Sabine's formula for the additional absorption.

The reverberation times T_{15} and T_{15-30} for all four octave bands, averaged over the five main-floor locations, are shown in Fig. 1 for the original Hall and the

[3] All seating designations refer to the seating plan in effect after the reopening of the Hall in the fall of 1965. The main-floor average was performed on the results obtained for seats along the center aisle at rows J, R, Y, FF, and NN.

[4] M. R. Schroeder, "New Method of Measuring Reverberation Time," J. Acoust. Soc. Am. 37, 409–412 (1965).

[5] B. S. Atal and M. R. Schroeder, J. Acoust. Soc. Am. (to be published).

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms

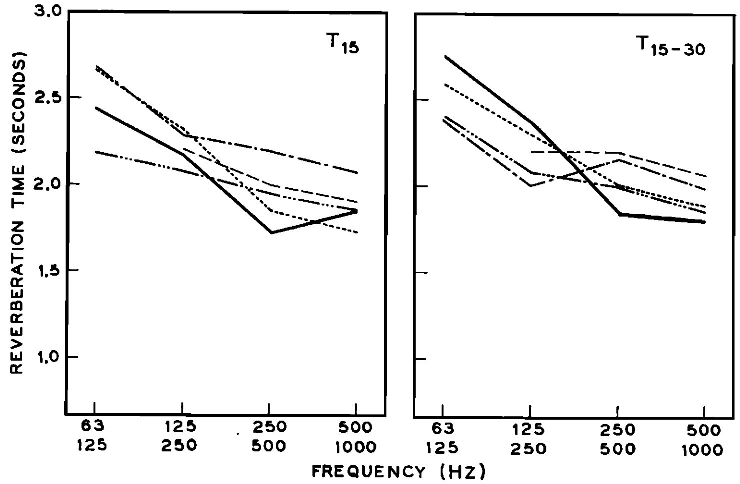

FIG. 1. Reverberation time, in octave bands, averaged over five main-floor positions for the original Hall and the Hall after Phases I–IV. T_{15} is based on the decay over the first 15 dB, and T_{15-30} is based on the decay between −15 and −30 dB. — — —: Original Hall. —·—: After Phase I. - - - -: After Phase II. —· · ·—: After Phase III. ——: After Phase IV.

Hall after Phases I–IV. The over-all increase of T_{15-30} at low frequencies due to the alterations can be explained by the progressive closing of the suspended ceiling, which was relatively transparent for low frequencies in the original Hall. On the other hand, the over-all decrease of T_{15-30} at midfrequencies is largely due to the absorptive treatment of the rear walls in Phase II. T_{15-30} was found to be relatively independent of position for all phases. This is to be expected since there is more diffusion for the later portions of the decay, and therefore spatially more uniform reverberation.

Measurements of the reverberation time made by us and others[6] in the original Hall using noise and pistol shots yielded a reverberation time of 2.5 sec for the frequency range 125–500 Hz, which is slightly higher than the present result of $T_{15}=2.2$ sec (see Fig. 1).

The importance of the initial reverberation time[7] for the subjective feeling of reverberation was confirmed in subjective experiments,[8] in which dry music and speech signals were reverberated nonexponentially, and the resulting test stimuli were compared with the same signals reverberated exponentially. These experiments indicated that the *initial* reverberation time T_{15} of the nonexponentially reverberated stimulus is subjectively equivalent to the reverberation time of the exponentially reverberated signal. This result is supported[8] by the fact that for Philharmonic Hall, as well as for another hall measured by the same method, T_{15} rather than T_{15-30} corresponds to the reverberation time of a subjectively equivalent exponential reverberation process simulated on the computer.

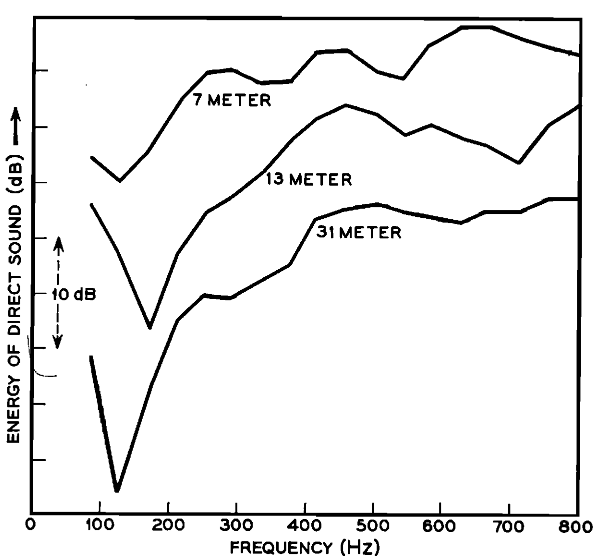

FIG. 2. Energy of the direct sound at various locations along the center aisle of the main floor. Parameter: distance between loudspeaker and microphone in meters.

B. Direct Energy

It has been found that sound waves traveling directly from a source on stage to a point on the main floor of a concert hall are subject to low-frequency attenuation in excess of the inverse square law at frequencies between 100 and 400 Hz, with a maximum loss near 200 Hz (Refs. 9–11). The curves in Fig. 2 represent the frequency response of the direct sound received at sev-

[6] L. L. Beranek, F. R. Johnson, T. J. Schultz, and B. G. Watters, "Acoustics of Philharmonic Hall, New York during Its First Season," J. Acoust. Soc. Am. **36**, 1247–1262 (1964).

[7] R. H. Bolt and P. E. Doak, "Tentative Criterion for the Short-Term Transient Response of Auditoria," J. Acoust. Soc. Am. **22**, 507–509 (1950).

[8] B. S. Atal, M. R. Schroeder, and G. M. Sessler, "Subjective Reverberation Time and Its Relation to Sound Decay," Paper G32 in *Proceedings of the Fifth International Congress on Acoustics, 1965, Liège*, D. E. Commins, Ed. (Imprimerie Georges Thone, Liège, 1965), Vol. 1b.

[9] G. M. Sessler, B. S. Atal, M. R. Schroeder, and J. E. West, "Acoustical Measurements in Philharmonic Hall (New York)," J. Acoust. Soc. Am. **36**, 1011 (A) (1964).

[10] T. J. Schultz and B. G. Watters, "Propagation of Sound across Audience Seating," J. Acoust. Soc. Am. **36**, 885–896 (1964).

[11] G. M. Sessler and J. E. West, "Sound Transmission over Theatre Seats," J. Acoust. Soc. Am. **36**, 1725–1732 (1964).

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms

eral main-floor locations progressively more distant from the stage. Parameter is the distance between loudspeaker and microphone. A deficiency at low frequencies that increases with increasing distance is noted. In contrast, the frequency response for locations on the second terrace is relatively flat. The attenuation has been explained[11] as a result of two effects: (1) a vertical "resonance" in the gaps between the rows of seats at a frequency for which the wavelength corresponds from two to four times the height of the seats, leading to strong selective attenuation at about 200 Hz; and (2) a diffraction effect around the upper edges of the seats, leading to broad-band attenuation in the frequency range from 100 to 400 Hz. This "seat effect" is probably common to all auditoriums where orchestra seats are not steeply raked.

C. Reflections from the Suspended Ceiling (Clouds)

Experiments in Philharmonic Hall[12] and on scale models of the suspended ceiling,[12,13] performed prior to any alterations of the Hall, indicated that the suspended ceiling did not efficiently reflect frequencies below about 300 Hz. The realignment of the ceiling (closing the gaps between the panels and elevating parts of the suspended ceiling) was intended to correct this deficiency.

Figure 3 shows the main-floor average[3] of the energy of the cloud reflections for the original Hall and the Hall after Phases I–IV. This frequency response was obtained from the output of the omnidirectional microphone by integrating over a 12-msec interval centered around the arrival time of the reflections from the clouds for each position. Due to the modifications made on the suspended ceiling in Phases I and III, the intensity of the cloud reflections has been increased at low frequencies and decreased at high frequencies.

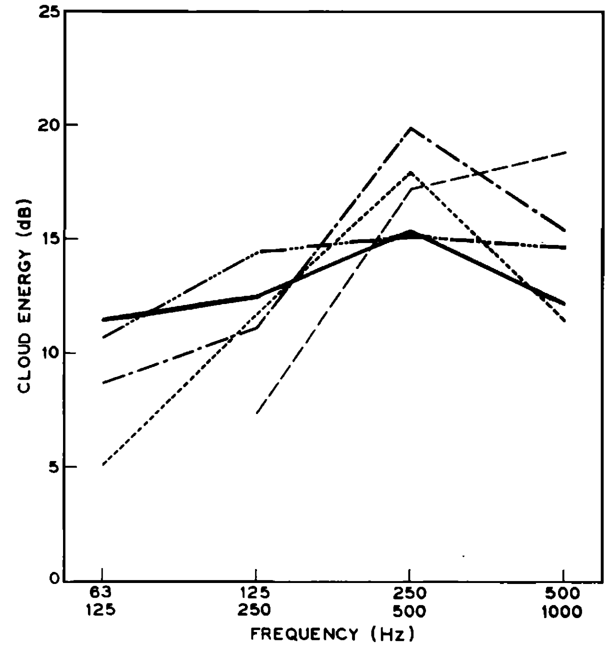

FIG. 3. Energy of cloud reflections in octave bands measured at earlevel and averaged over five main-floor positions for the original Hall and the Hall after Phases I–IV. — — —: Original Hall. —·—: After Phase I. - - - -: After Phase II. —· · ·—: After Phase III. ——: After Phase IV.

D. Early Energy

The early energy is defined as the energy of the direct sound and that arriving within 50 msec. The main-floor average of the early energy in octave bands is shown in Fig. 4. The Figure shows that the *spectral balance* of the early sound was improved due to each phase of the alteration program, with the greatest improvements achieved by Phase III. These improvements can be explained by corresponding changes in the cloud energy and in the energy of other early reflections. For example, the decrease in high-frequency energy in Phase I is due to the diminished cloud reflections in the octave band 500–1000 Hz, and the increase in low-frequency energy in Phase III is due to the new stage enclosure, which provided reflections from higher portions of the stage that are not subject to the low-frequency seat attenuation. This shows that the deficiencies in the early energy owing to the seat attenuation may be overcome if other early reflections are not deficient in low-frequencies.

Because of the importance of the early energy for subjective listening, the relative increase of low-frequency early sound energy may be responsible for the

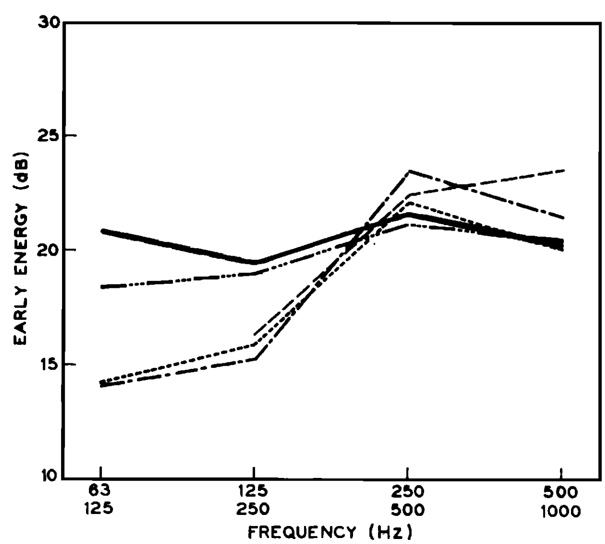

FIG. 4. Energy of the early sound in octave bands averaged over five main-floor positions for the original Hall and the Hall after Phases I–IV. — — —: Original Hall. —·—: After Phase I. - - - -: After Phase II. —· · ·—: After Phase III. —— :After Phase IV.

[12] B. G. Watters, L. L. Beranek, F. R. Johnson, and I. Dyer, "Reflectivity of Panel Arrays in Concert Hall," Sound—Its Uses and Control 2, No. 3, 26–30 (1963).

[13] E. Meyer and H. Kuttruff, "Reflexionseigenschaften durchbrochener Decken," Acustica 13, 183–186 (1963).

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms

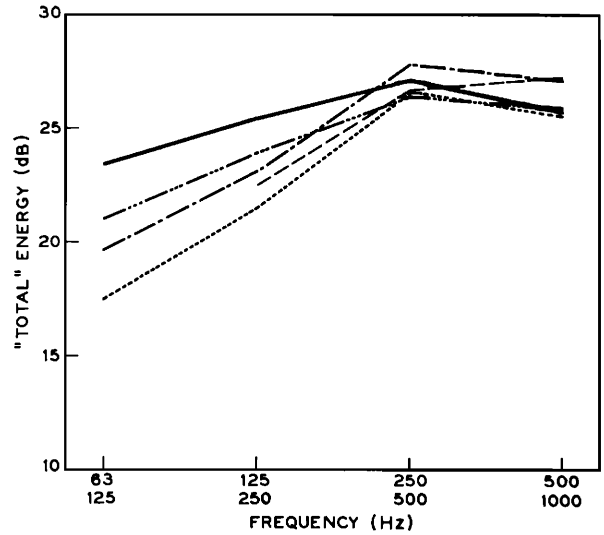

FIG. 5. Total energy in octave bands, averaged over five main-floor positions for the original Hall and the Hall after Phases I–IV. — — —: Original Hall. —·—: After Phase I. - - - -: After Phase II. —· · ·—: After Phase III. ——: After Phase IV.

improved audibility of the low-pitched instruments on the main floor of the Hall.

E. "Total" Energy

The "total" energy is defined as the energy arriving within 1 sec of the direct sound. The total energy, averaged over *all positions*, was not changed significantly, due to the alterations of the Hall. Figure 5 shows the total energy, averaged over *five main-floor positions*,[3] for the original Hall and the Hall after Phases I–IV. For the original Hall, the frequency response showed a 4.5-dB difference between the octaves 125–250 and 500–1000 Hz. For the Hall after Phase IV, this difference is reduced to 0.5 dB. This improvement is due primarily to the same factors that are responsible for the flattening of the frequency response of the early energy.

F. Ratio of Early-to-Reverberant Energies

Figure 6 shows the ratio of early-to-reverberant energies, averaged over the five main-floor locations, for the original Hall and the Hall after Phases I–IV. This ratio was practically unaffected above 250 Hz by the alterations in the Hall. If averaged over all positions, this ratio is almost independent of frequency and close to −2.1 dB, which is the expected value for a hall with a reverberation time of 2.0 sec and an exponential decay.

G. Directional Distribution Factor of the Early Sound Energy

The directional distribution factor of the early energy is defined as S_l/S_{nl} where S_l is the ratio of early-to-reverberant energies arriving laterally and S_{nl} is the same ratio for nonlaterally arriving reflections. If the reverberant energy is uniformly distributed, $S_l/S_{nl}=1$ means a uniform angular distribution of the early energy, $S_l/S_{nl}>1$ indicates a preponderance of early sound from the sides, and $S_l/S_{nl}<1$ indicates relatively strong early sound from other (nonlateral) directions.

Since, in general, measurements were taken with an omnidirectional and a laterally oriented directional microphone, the directional distribution factor has to be determined as follows. The early energy received at any point in the Hall by the omnidirectional microphone can be divided into two parts according to the equation

$$E_o=E_l+E_{nl}, \tag{1}$$

where subscripts o and l refer to omnidirectional and lateral microphone directivities and nl to a directivity complementary to that of l. For the following discussion, it is assumed[14] that the *reverberant* energy R is uniformly distributed over the solid angle, i.e., R_o, R_l, and R_{nl} are proportional to the solid angles Ω_o, Ω_l, and Ω_{nl} associated with these energies for any point in the Hall; therefore,

$$R_o/\Omega_o=R_l/\Omega_l=R_{nl}/\Omega_{nl}. \tag{2}$$

Dividing Eq. 1 by R_o/Ω_o yields

$$S_o\Omega_o=S_l\Omega_l+S_{nl}\Omega_{nl}, \tag{3}$$

where S_o has been substituted for E_o/R_o, etc. (This normalization makes Eq. 3 independent of the calibration of the individual microphones.) Then, the above-

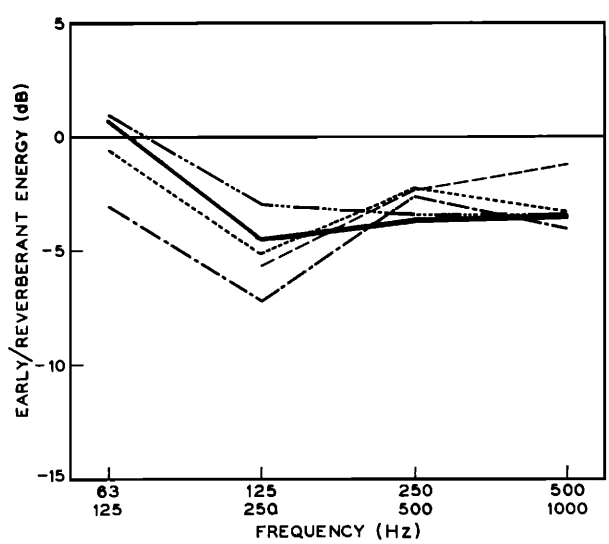

FIG. 6. Ratio of early-to-reverberant energies, averaged over five main-floor positions for the original Hall and the Hall after Phases I–IV. — — —: Original Hall. —·—: After Phase I. - - - -: After Phase II. —· · ·—: After Phase III. ——: After Phase IV.

[14] This assumption was checked by comparing measured values of R_0/Ω_0 and R_l/Ω_l for several points in the Hall. For each point, the two values were found to be equal within ±1 dB.

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms

defined distribution factor is

$$S_l/S_{nl}=S_l\Omega_{nl}/(S_o\Omega_o-S_l\Omega_l). \tag{4}$$

In Philharmonic Hall, measurements were made with an omnidirectional microphone and a unidirectional microphone (with a solid angle of pickup of 45°) pointed towards one side wall. The directional distribution factor of the early sound is plotted in Fig. 7 for the Hall after Phases I and IV. The results in Fig. 7 indicate a preponderance of early energy from the nonlateral direction on the main floor after Phase I. For the Second Terrace locations, S_l/S_{nl} is larger by 4–10 dB, indicating the presence of strong early reflections from the side. This objective difference between the main floor and the Second Terrace may in part have been responsible for the difference in subjective quality when listening to music in these locations. For the Hall after Phase IV, the directional distribution of the early energy is more uniform throughout the Hall, but there are still relatively more lateral reflections on the Second Terrace than on the main floor in the midfrequency range (250–1000 Hz).

H. Echoes

Echoes were audible in the front part of the Hall before and after Phase I of the alterations. Short tone bursts (duration 3 msec), similar in shape to the bursts used for the other measurements, were radiated with directional loudspeakers towards various sections of the Hall, and the reflected sound energy was received with an "unidirectional" microphone and recorded. This method made it possible to trace the echoes to reflections from the upper rear walls and the balcony fronts. These echoes arrived with a delay of 200–300 msec in the front part of the Hall. Figures 8(a) and (b) show echo responses of the Hall before and after Phase II of the alteration program, respectively. The responses have been smoothed by an RC network with a time constant of 50 msec. An evaluation of Fig. 8 indicates an average decrease of 7 dB of the strong echoes that arrive with a delay of 200–300 msec.

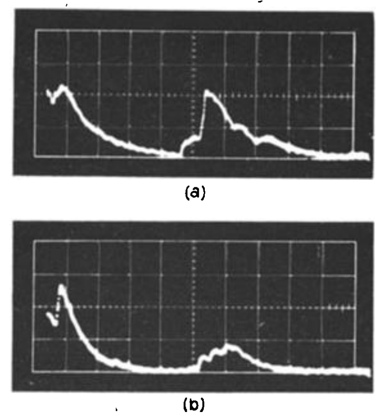

FIG. 8. Echo response of the Hall. (a) Response before Phase II of the alteration program. (b) Response after Phase II. Horizontal scale: 50 msec per major division.

To obtain a subjectively meaningful figure for the echo reduction, the impulse response of the Hall *before* alterations was fed into a digital computer, where the echoes were attenuated by 1–10 dB in steps of 1 dB, and the resulting responses were compared in listening tests with the response *after* alterations. The response after alterations was found to be subjectively equal to the response before alterations, if the echoes in the latter were attenuated by 7 dB, which is in agreement with the objective results employing a 50-msec averaging network.

I. Ambient-Noise Measurements

The ambient-noise level was measured for the Hall after Phase IV at two locations on the main floor (rows E and EE center) with the air-conditioning system on and off. The measurements were made with a Brüel and Kjær type 2203 sound-level meter in conjunction with the octave filter set type 1613. The results of these

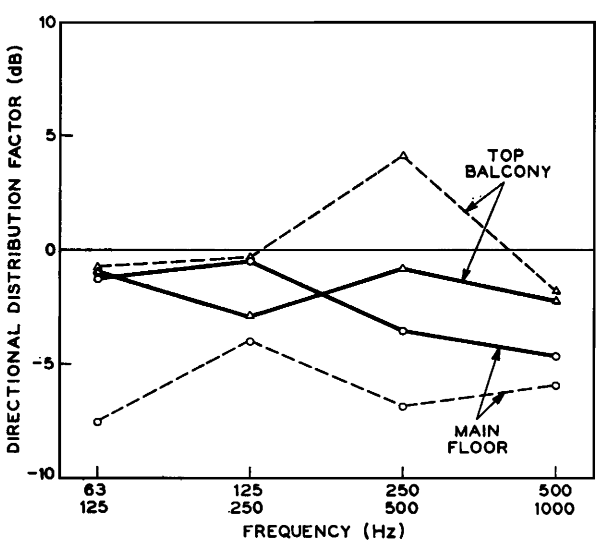

FIG. 7. Main-floor and Second Terrace average of the directional distribution factor of the early energy for the Hall after Phases I and IV. — — —: After Phase I. ——: After Phase IV.

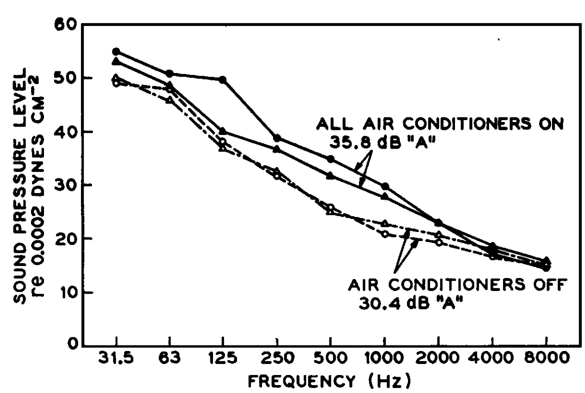

FIG. 9. Noise level in the Hall after Phase IV measured at two positions with the air conditioners on and off. △—·—△, ▲——▲: E center. ○— — —○, ●——●: EE center.

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms

measurements are shown in Fig. 9. The A-weighted values, which are also indicated in the Figure, equal 30.4 and 35.8 dBA for the air conditioning off and on, respectively.

The measurements, although made during the evening rush hour, are not believed to be influenced by noise originating outside the building.

III. SUMMARY AND CONCLUSIONS

The measurements performed in Philharmonic Hall have shown the following. (1) The reverberation times T_{15} and T_{15-30} in the midfrequency range for the main floor of the original Hall are 1.9 and 2.1 sec, respectively. In the present state of the Hall, both reverberation times are equal and about 1.8 sec; thus, the decay process has become more exponential. (2) The energy of the reflections from the suspended ceiling and the early and total energies were deficient in low frequencies prior to the alterations; now they are relatively independent of frequency. (3) For an early state of the Hall, the early energy arrived primarily from nonlateral directions on the main floor and was equally distributed on the second terrace. For the present state of the Hall, the ratio of lateral to nonlateral early energies is much closer to unity, but is is still slightly higher on the second terrace than on the main floor in the midfrequency range. (4) Echoes from the rear walls present after Phase I were reduced by about 7 dB, resulting in a more exponential reverberation process and fewer and less-intense echoes.

In subjective experiments, it was found that the initial reverberation time, rather than the final reverberation time, is of importance; therefore, the relatively low value of the initial reverberation time could be responsible for the subjective "dryness" of the Hall. The observed increase of the low-frequency energy of the early and total sound due to the alteration seems to be responsible for the subjectively noticeable improvement in the audibility of low frequencies.

In Philharmonic Hall, as in many other concert halls, the subjective acoustical quality on the higher balconies is superior to that on the main floor. The major objective parameter that shows a significant difference for the main floor and the terrace locations is the directional distribution of the early energy. It is therefore tentatively concluded that the directional distribution of early reflections is a significant contributing factor to acoustical quality.

It is hoped that additional correlations between subjective qualities and objective parameters can be established by applying the computer method of measurement and evaluation to other concert halls with known subjective characteristics.

ACKNOWLEDGMENTS

We are indebted to Dr. H. Kuttruff and A. M. Noll, for helpful discussions, and to Janice Horn and Susan Murphy, for writing the computer program. Thanks are also due to J. H. Krommeyer and D. J. MacLean, for assistance with the concert-hall measurements.

Downloaded 22 Aug 2012 to 190.114.208.143. Redistribution subject to ASA license or copyright; see http://asadl.org/terms