Symposium on Wire Transmission of Symphonic Music and Its Reproduction in Auditory Perspective

Basic Requirements*

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The fundamental requirements involved in a system capable of picking up orchestral music, transmitting it a long distance, and reproducing it in a large hall, are discussed in this paper.

IN THIS electrical era one is not surprised to hear that orchestral music can be picked up in one city, transmitted a long distance, and reproduced in another. Indeed, most people think such things are commonplace. They are heard every night on the radio. However, anyone who appreciates good music would not admit that listening even to the best radio gives the emotional thrill experienced in the concert hall. Nor is it evident that a listener in a small room ever will be able to get the same effect as that experienced in a large hall, although it must be admitted that such a question is debatable. The proper answer will involve more than a consideration of only the physical factors.

This symposium describes principles and apparatus involved in the reproduction of music in large halls, the reproduction being of a character that may give even greater emotional thrills to music lovers than those experienced from the original music. This statement is based upon the testimony of those who have heard some of the few concerts reproduced by the apparatus which will be described in the papers of this symposium.

It is well known that when an orchestra plays, vibrations which are continually changing in form are produced in the air of the concert hall where the orchestra is located. An ideal transmission and reproducing system may be considered as one that produces a similar set of vibrations in a distant concert hall in which is executed the same time-sequence of changes that takes place in the original hall. Since such changes are different at different positions in the hall, the use of such an ideal system implies that at corresponding positions in the

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two halls this time-sequence should be the same. Obviously, this never can be true at every position unless the halls are the same size and shape; corresponding positions would not otherwise exist. Let us consider the case where the two halls are the same size and shape and also have the same acoustical properties. Let us designate the first hall in which the music originates by *O*, and the second one in which the music is reproduced by *R*. What requirements are necessary to obtain perfect reproduction from *O* into *R* such that any listener in any part of *R* will receive the same sound effects as if he were in the corresponding position in *O*?

Suppose there were interposed between the orchestra and the audience a flexible curtain of such a nature that it did not interfere with a free passage of the sound, and which at the same time had scattered uniformly over it microphones which would pick up the sound waves and produce a faithful electrical copy of them. Assume each microphone to be connected with a perfect transmission line which terminates in a projector occupying a corresponding position on a similar curtain in hall *R*. By a perfect transmission line is meant one that delivers to the projector electrical energy equal both in form and magnitude to that which it receives from the microphone. If these sound projectors faithfully transform the electrical vibrations into sound vibrations, the audience in hall *R* should obtain the same effect as those listening to the original music in hall *O*.

Theoretically, there should be an infinite number of such ideal sets of microphones and sound projectors, and each one should be infinitesimally small. Practically, however, when the audience is at a considerable distance from the orchestra, as usually is the case, only a few of these sets are needed to give good auditory perspective; that is, to give depth and a sense of extensiveness to the source of the music. The arrangement of some of these simple systems, together with their effect upon listeners in various parts of the hall, is described in the paper by Steinberg and Snow (page 245).

In any practical system it is important to know how near these ideal requirements one must approach before the listener will be aware that there has been any degradation from the ideal. For example, it is well known that whenever a sound is suddenly stopped or started, the frequency band required to transmit the change faithfully is infinitely wide. Theoretically, then, in order to fulfill these ideal requirements for transmitting such sounds, all three elements in the transmission system should transmit all possible frequencies without change. Practically, because of the limitations of hearing, this is not necessary. If the intensities of some of the component frequencies required to represent

such a change are below the threshold of audibility it is obvious that their elimination will not be detected by the average normal ear. Consequently, for highgrade reproduction of sounds it is obvious that, except in very special cases, the range of frequencies that the system must transmit is determined by the range of hearing rather than by the kind of sound that is being reproduced.

Tests have indicated that, for those having normal hearing, pure tones ranging in frequency from 20 to 20,000 cycles per second can be heard. In order to sense the sounds at either of these extreme limits, they must have very high intensity. In music these frequencies usually are at such low intensities that the elimination of frequencies below 40 c.p.s. and those above 15,000 c.p.s. produces no detectable difference in the reproduction of symphonic music. These same tests also indicated that the further elimination of frequencies beyond either of these limits did begin to produce noticeable effects, particularly on a certain class of sounds produced in the orchestra. For example, the elimination of all frequencies above 13,000 c.p.s. produced a detectable change in the reproduced sound of the snare drum, cymbals, and castanets. Also, the elimination of frequencies below 40 c.p.s. produced detectable differences in reproduced music of the base viol, the bass tuba, and particularly of the organ.

Within this range of frequencies the system (the combination of the microphone, transmission line, and loud speaker) should reproduce the various frequencies with the same efficiency. Such a general statement sounds correct, but a careful analysis of it would reveal that when any one tried to build such a system or tried to meet such a requirement he would have great difficulty in understanding what it meant.

For example, for reproducing all the frequencies within this band, a certain system may be said to have a uniform efficiency when it operates between two rooms under the condition that the pressure variation at a certain distance away from the sound projector is the same as the pressure variation at a certain position in front of the microphone. It is obvious, however, that in other positions in the two rooms this relation would not in general hold. Also, if the system were transferred into another pair of rooms the situation would be entirely changed. These difficulties and the way they were met are discussed in the papers of this symposium that deal with loud speakers and microphones (p. 259) and with methods of applying the reproducing system to the concert hall (p. 301). It will be obvious from these papers that the criterion for determining the ideal frequency characteristics to be given to the system is arbitrary within certain limits. However, solving the problem according to criteria adopted produced a system that gave very satisfactory results.

Besides the requirement on frequency response just discussed, the system also must be capable of handling sound powers that vary through a very wide range. If this discussion were limited to the type of symphonic music that now is produced by the large orchestras, this range would be about 10,000,000 to 1, or 70 decibels. To reproduce such music then, the system should be capable of handling the smallest amount of power without introducing extraneous noises approaching it in intensity, and also reproduce the most intense sounds without overloading any part of the transmission system. However, this range is determined by the capacities of the musical instruments now available and the man power that conveniently can be grouped together under one conductor. As soon as a system was built that was capable of handling a much wider range, the musicians immediately took advantage of it to produce certain effects that they previously had tried to obtain with the orchestra alone, but without success because of the limited power of the instruments themselves. For these reasons it seems clear that the desirable requirements for intensity range, as well as those for frequency range, are determined largely by the ear rather than by the physical characteristic of any sound. An ideal transmission should, without introducing an extraneous audible sound, be capable of reproducing a sound as faintly as the ear can hear and as loudly as the ear can tolerate. Such a range has been determined with the average normal ear when using pure tones. The results of recent tests are shown in Fig. 1.

The ordinates are given in decibels above the reference intensity which is 10^{-16} watts per square centimeter. The values are for field intensities existing in an air space free from reflecting walls. The most intense peaks in music come in the range between 200 and 1000 c.p.s. Taking an average for this range it may be seen that there is approximately a 100-db range in intensity for the music, provided about 10 db is allowed for the masking of sound in the concert hall even when the audience is quietest.

The music from the largest orchestra utilizes only 70 db of this range when it plays in a concert hall of usual size. To utilize the full capabilities of the hearing range the ideal transmission system should add about 10 db on the *pp* side and 20 db on the *ff* side of the range. The capacity of the sound projectors necessary to reach the maximum allowable sound that the ear can tolerate varies with the size of the room. A good estimate can be obtained by the following consideration.

If T is the time of reverberation of the hall in seconds, E the power of the sound source in watts, I the maximum energy density per cubic

centimeter in joules, and V the volume of the hall in cubic centimeters, then it is well known that

$$I = \frac{1}{6 \log_e 10} \cdot \frac{ET}{V}. \qquad (1)$$

Measurements have shown that when the sound intensity in a free field reaches about 10^{-4} watts per square centimeter, the average person begins to *feel* the sound. This maximum value is approxi-

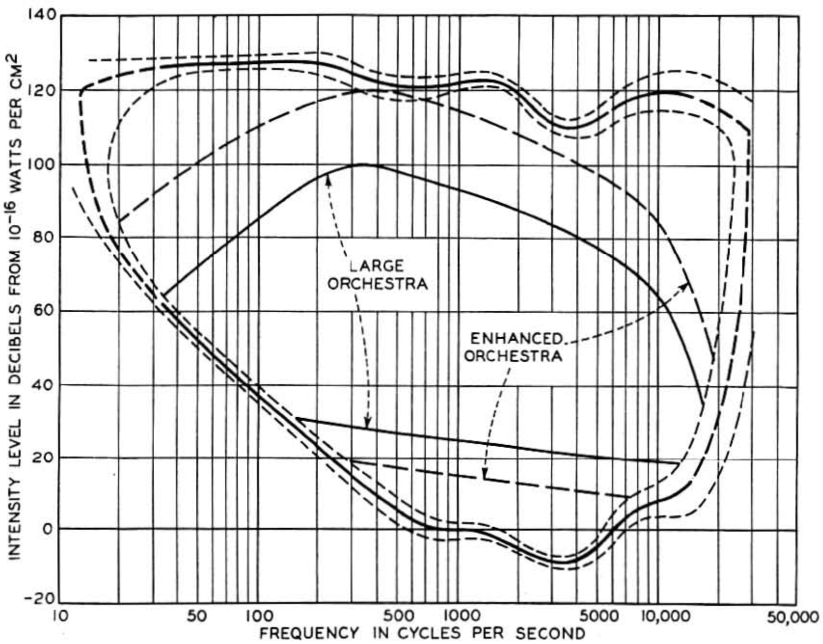

Fig. 1—Limits of audible sound as determined by recent tests.

mately the same for all frequencies in the important audible range. Any higher intensities, and for some persons somewhat lower intensities, become painful and may injure the hearing mechanism. This intensity corresponds to an energy density I of 3×10^{-9} joules. Using this figure as the upper limit to be tolerated by the human ear, then, the maximum power of the sound source must be given by

$$E = 4.1 \times 10^{-8} \frac{V}{T}. \qquad (2)$$

For halls like the Academy of Music in Philadelphia and Carnegie Hall in New York City, in which the volume V is approximately 2×10^{10} cubic centimeters and the reverberation time about 2 seconds,

E, the power of the sound source, is approximately 400 watts. For other halls it may be seen that the power required for this source is proportional to the volume of the hall and inversely proportional to the reverberation time. A person would experience the sense of *feeling* when closer than about 10 meters to such a source of 400 watts power, even in free open space. Hence it would be unwise to have seats closer than 10 or 15 meters from the stage when such powers are to be used.

These, then, are the general fundamental requirements for an ideal transmission system. How near they can be realized with apparatus that we now know how to build will be discussed in the papers included in this symposium.

A system approximately fulfilling these requirements was constructed and used to reproduce the music played by the Philadelphia Orchestra. The first public demonstration was given in Constitution Hall, Washington, D. C., on the evening of April 27, 1933, under the auspices of the National Academy of Sciences. At that time, Dr. Stokowski, Director of the Philadelphia Orchestra, manipulated the electric controls from a box in the rear of Constitution Hall while the orchestra, led by Associate Conductor Smallens, played in the Academy of Music in Philadelphia.

Three microphones of the type described in the paper by Wente and Thuras (p. 259) were placed before the orchestra in Philadelphia, one on each side and one in the center at about 20 feet in front of and 10 feet above the first row of instruments in the orchestra. The electrical vibrations generated in each of these microphones were amplied by voltage amplifiers and then fed into a transmission line which was extended to Washington by means of telephone cable. The construction of these lines, the equipment used with them, and their electrical properties, are described in the paper by Affel, Chesnut, and Mills (p. 285). In Constitution Hall at Washington, D. C., these transmission lines were connected to power amplifiers. The type of power amplifiers and voltage amplifiers used are described in the paper by Scriven (p. 278). The output of these amplifiers fed three sets of loud speakers like those described in the paper by Wente and Thuras. They were placed on the stage in Constitution Hall in positions corresponding to the microphones in the Academy of Music, Philadelphia.

Judging from the expression of those who heard this concert, the development of this system has opened many new possibilities for the reproduction and transmission of music that will create even a greater emotional appeal than that obtained when listening to the music coming directly from the orchestra through the air.