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PERFECT QUALITY AND AUDITORY PERSPECTIVE IN THE TRANSMISSION AND REPRODUCTION OF MUSIC[1]

By Dr. FRANK B. JEWETT

BELL TELEPHONE LABORATORIES

IT is quite impossible in the short space of the fifteen or twenty minutes allotted to me to attempt anything in the way of detail, either in the matter of the scientific principles involved in the apparatus and equipment of this particular system of music transmission or in the elaborate arrangement of parts involved in the demonstration to be given in Constitution Hall next Thursday evening. As a matter of fact, all the scientific material has been or will be incorporated in various technical papers. Further, the demonstrations which Dr. Harvey Fletcher is proposing to give at the time of the Thursday demonstration will be more illuminating than anything which I could hope to reproduce here.

All that I propose to do, therefore, is to outline briefly the fundamentals of the problem, the extent to which we have succeeded in solving them, and the general arrangement of parts which will be employed in the transmission and reproduction of a complete symphonic concert from the stage of the Academy of Music in Philadelphia to the stage of Constitution Hall in Washington.

For the perfect pick-up, transmission and reproduction of orchestral music a system is needed, such that the sound reproduced in the ears of the listener is the same as that which would be produced in his ears if he were listening to the orchestra directly. In other words, the frequency, intensity and phase relations of the sound in each ear must be accurately reproduced in order best to convey the frequency and intensity range of the sounds and the spatial relations of the instruments. So far as we now know, this can be done

[1] Presented to the annual meeting of the National Academy of Sciences, Washington, D. C., April 25.

only by means of a binaural telephone system, using two head receivers for each listener. In other words, to obtain what might be called an acoustic facsimile, a separate telephone system must be used for each ear of the listener. Such an arrangement was necessarily employed in working out the arrangements which have been developed, although for obvious reasons it was never contemplated that such a system could ever be used for a general audience.

Although such a facsimile can not be produced by means of loud-speaking telephones, it is possible by their means to reproduce music which has auditory perspective, and which in many ways gives just as pleasing an effect as though it were a perfect facsimile. As an illustration of how this might be accomplished, it is possible to imagine a system of microphones and sound projectors which will approach facsimile reproduction as follows.

Suppose the stage of the music hall is acoustically insulated so that the only sound reaching the audience is that coming through the opening occupied by the curtain when it is lowered. If now a large number of microphones are distributed over the plane occupied by the curtain when it is lowered and each microphone is connected to a loud speaker similarly placed before the audience where the music is to be reproduced, then if the microphones, the loud speakers and the connecting lines have the right characteristics, the audience should receive sound which is a very close approximation to the original. In such a system the microphones must be so small as not to interfere with the free passage of the sound waves and must produce an electrical facsimile of the sound waves in front of them. Similarly, each of the connecting lines must be distortionless. The loud speakers must be very small and must produce an acoustic facsimile of the electrical waves. At the present time, we do not know how to produce loud speakers of this character. Even if we did know how to produce them, the expense involved would be prohibitive on account of the amount and complexity of apparatus required and of the cost of the multi-channel connecting lines. Fortunately, however, experience has shown that a very close approximation to complete facsimile reproduction can be obtained by using a three-channel system. With such a system the auditory illusion is substantially complete except for those persons sitting very near to the stage.

Broadly speaking, the frequency range which is needed to secure perfect reproduction is the entire frequency range that is audible to the human ear. However, tests with reproduced orchestral music have shown that the elimination of the frequency range below 30 or 40 cycles per second and that above 15,000 cycles per second is hardly detectable. These eliminated frequencies are very close to the audible limits for the average person.

A full-sized symphonic orchestra is capable of producing sound through an intensity range of about 65 or 70 db. For perfect reproduction any electrical system to be satisfactory must be capable of handling an intensity range of at least this amount. The range that a system can handle is determined by the difference between the noise level and the overload level. When a system capable of handling a greater intensity range than that ordinarily produced by an orchestra was finally developed musicians were quick to take advantage of it as a means of increasing the sound intensity during crescendo passages above normal and in decreasing the intensity during very soft passages below normal. This indicates apparently that the intensity range, which an ideal system should be capable of handling, is set by the range between the loudest sounds that a listener can hear comfortably and the faintest sounds that he can hear in a quiet audience. This range is somewhere between 80 and 100 db, depending upon the character of the music. Roughly, such an ideal system will produce maximum sounds in crescendo periods about ten times as loud as those which a one hundred piece orchestra is capable of producing directly.

Characteristics of the Pick-up Microphones Employed and Their Location

The characteristics of the microphones which have been developed for this reproducing system are described in two papers entitled, "Moving-Coil Telephone Receivers and Microphones," by Wente and Thuras, and "A Sensitive Moving-Coil Microphone of High Quality," by Thuras.

Characteristics of Loud Speakers Employed and Their Location

Each loud speaker assembly employed in reproducing transmitted music consists of three units. One of these units is of large dimensions and is designed for the perfect reproduction of frequencies below 300 cycles per second. The remaining two units, which are small and alike, are designed for the perfect reproduction of all frequencies above 300 cycles per second. These two small units are mounted on top of the low frequency unit and the combination of the three units is so designed and arranged that the entire frequency band of sound is distributed uniformly throughout the hall.

Characteristics of Power Amplifiers

Time does not permit any detailed description of the power amplifiers which it is necessary to employ in order to obtain the requisite amount of energy. Suffice to say, these amplifiers must have substantially flat amplification characteristics for all frequencies at all intensity levels and must be capable not only of maintaining continuously these characteristics for the normal sound range of the orchestra, but must also be capable of handling for short periods and without distortion the greatly increased sound range in crescendo passages.

QUASI-BINAURAL ARRANGEMENT EMPLOYED

As is shown in Fig. 1, three complete channels are used. Each channel consists of a microphone, amplifier, volume control, connecting line and loud speaker.

Hall. The volume control which Dr. Stokowski will use permits of changing the three channels simultaneously as a group or of changing each individually as he may elect in order to obtain any desired tonal coloring.

The response characteristic of the overall system is obviously dependent upon the acoustic properties of the rooms in which the sounds are picked up and reproduced. In order to obtain a proper overall characteristic, the loud speakers were put on the stage at the Academy of Music and connected to an electrical oscillator. The pick-up microphones were hung in their proper positions in front of the stage. The electrical power developed by the transmitters was

LOUD SPEAKER ARRANGEMENT

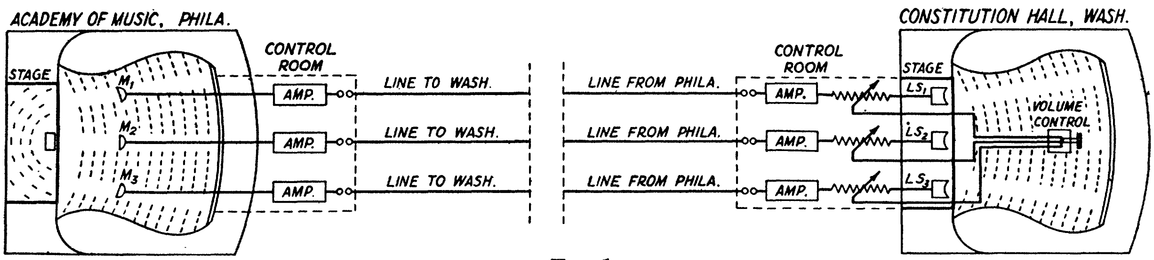

FIG. 1

In the Academy of Music in Philadelphia, the microphones are placed about ten feet in front of the stage and ten or twelve feet above the floor. These microphones are connected to loud speakers in corresponding positions on the stage of Constitution Hall, *i.e.,* the microphone at the left of the Philadelphia stage connects to a loud speaker at the left of the Washington stage, etc. Thus, the three channels, left, center and right, reproduce the sounds arising in corresponding positions on the Philadelphia stage.

METHOD OF VOLUME CONTROL WHICH DR. STOKOWSKI WILL EMPLOY

In the system to be demonstrated in Constitution Hall Thursday evening, provision is made for Dr. Stokowski to control the volume of sound from the loud speakers on the stage of Constitution Hall while seated at a monitoring position in the audience at Constitution Hall. He will also have facilities for communicating directly with the orchestra on the stage at the Academy of Music in Philadelphia. The general features of the plan for the demonstration are to transmit without change the program to Washington as it is picked up at Philadelphia. The unchanged program coming to Washington may then be changed at will by means of the volume control before reaching the loud speakers on the stage of Constitution

compared with the electrical power supplied to the loud speakers for sinusoidal waves in the frequency range 40 to 15,000 cycles per second. The system was then equalized so that the power ratio was a constant over the entire frequency range. Since each channel of the system is capable of furnishing a steady acoustic power of at least 35 watts at any frequency in the entire range, the three channels together are capable of furnishing at least 100 watts of power. In the middle of the frequency range several times this amount of power can be produced without distortion. When the energy frequency distribution of orchestral music is taken into account, it turns out, as was indicated earlier, that the system is capable of magnifying the total sound output of a one hundred piece orchestra about tenfold.

AUDIBLE FREQUENCY RANGE FOR MUSIC, SPEECH AND NOISE

As a matter of passing interest, Fig. 2 shows the audible frequency range for speech and for various kinds of noises and musical instruments which the system is capable of reproducing without noticeable distortion. As will be seen, these frequencies extend from the deep low notes of the bass viol and bass tuba to the high frequencies emanating from the snare drum, cymbals, violin, oboe, footsteps, hand-clapping

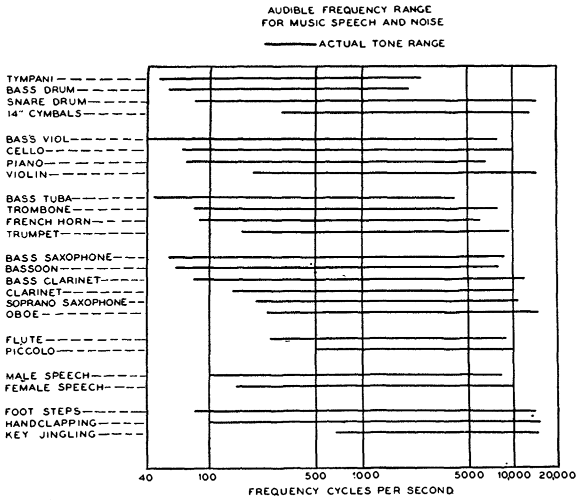

FIG. 2

and key-jingling, all of which are substantially near the upper limit of audible frequency for the average human ear.

TRANSMISSION LINES

The general route of the transmission lines, together with the location of the repeater or amplifier stations, is shown on Fig. 3. The distance between Philadelphia and Washington is approximately 140 miles and the transmission circuits are in lead-covered underground cable.

This figure also shows in schematic form the three separate channels required for the system just described. It also shows in rough schematic the energy level variations along the line. As will be seen, the energy amplification at each repeater station is about 50 db. In other words, at each repeater station the gradually weakened currents are enormously magnified to the end that the level of energy, as it is delivered at Constitution Hall, will be substantially the same as that at the Academy of Music.

The transmission lines themselves have substantially flat characteristics (± 1 db) over the entire frequency range from 40 cycles to 15,000 cycles per second.

Carrier transmission is employed between the tele-

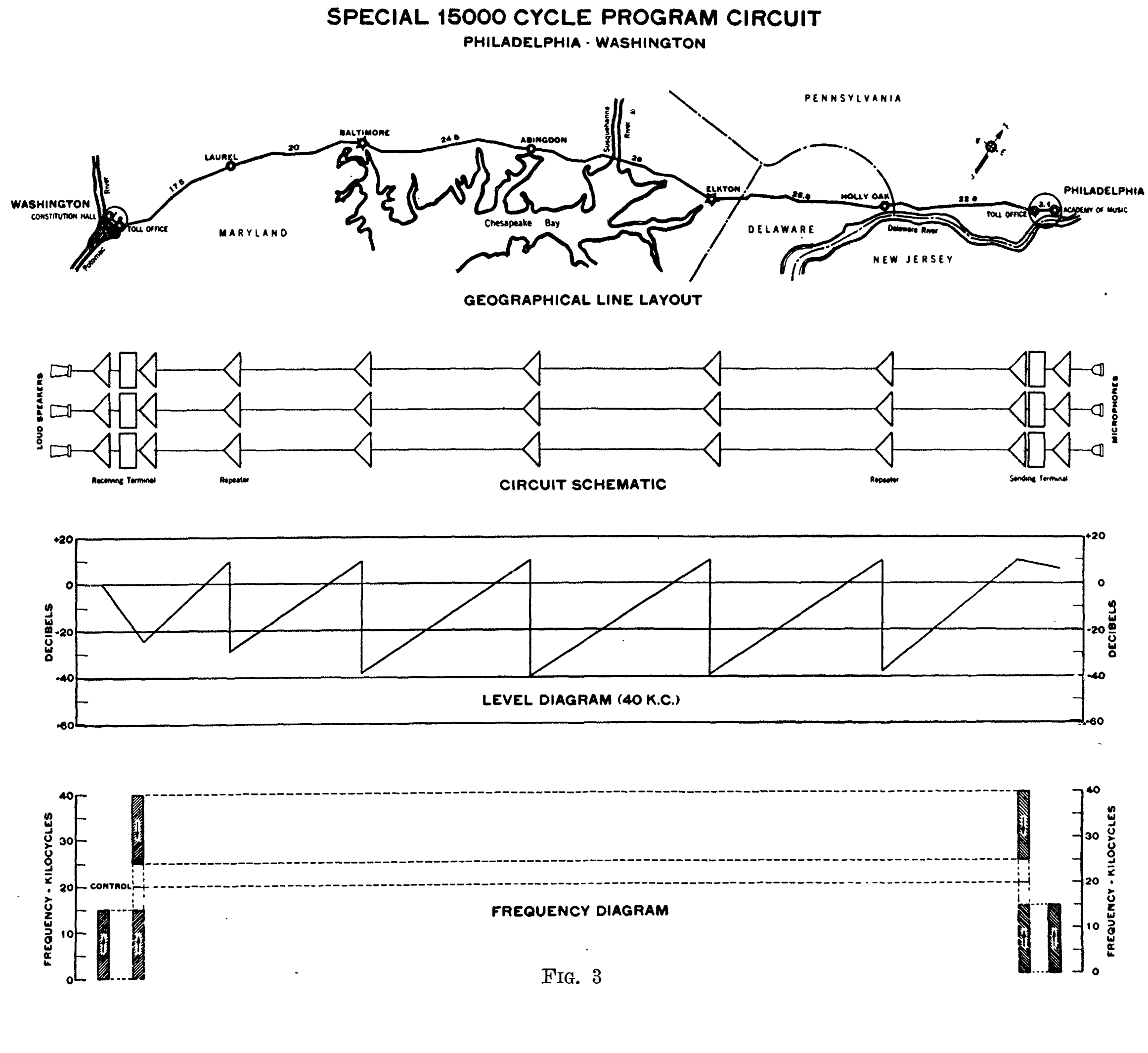

FIG. 3

phone toll offices in Philadelphia and Washington, a distance of approximately 140 miles. The carrier band lies in the frequency range between 25,000 and 40,000 cycles per second.

Fig. 4 shows a schematic of the special program circuit employed. As will be seen in this schematic and very stable with respect to wide power variations. The gain at each repeater is about 50 db. An important feature at each repeater point are the equalizers to adjust the degree of amplification proportional to the line loss for the different frequencies. This is essential since, as is well known, the higher frequen-

SCHEMATIC OF
SPECIAL 15000 CYCLE PROGRAM CIRCUIT
PHILADELHIA WASHINGTON

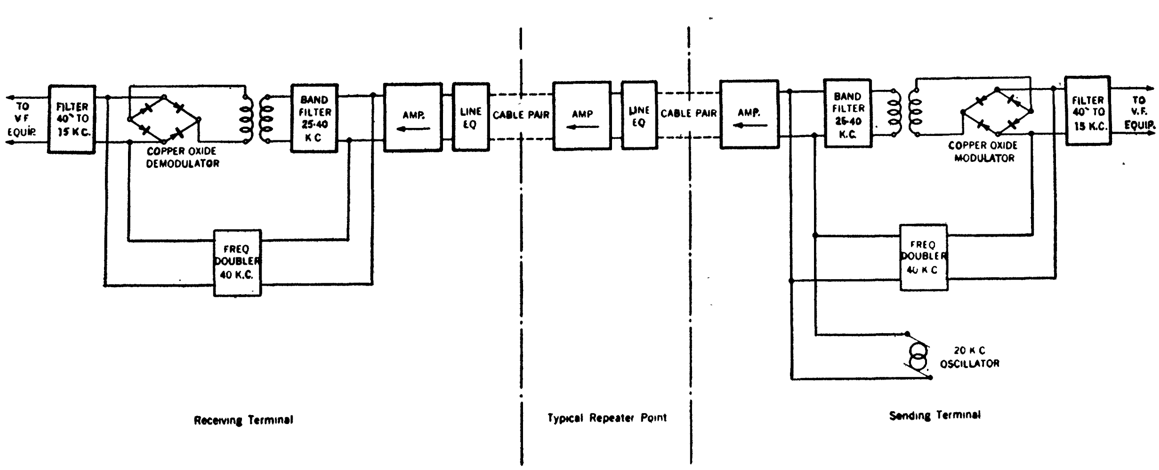

FIG. 4

and as will be referred to in a moment, accurate control of frequency and phase throughout the system and at its terminations is obtained by employing at the sending end a 20 kilocycle oscillator, part of whose output is transmitted over each of the three transmission channels. The 40 kilocycle carrier required for modulating at the transmitting end and for demodulating at the receiving end is obtained by employing a frequency doubling device at each terminal.

LINE LAYOUT

Three 16-gauge (1.29 mm) non-loaded pairs in an underground toll cable between Philadelphia and Washington are employed. Spare circuits are provided. Normally, the telephone circuits operated through this cable require only two intermediate repeater points (Elkton and Baltimore). Because of the extra high frequency transmission required in this music reproduction, three additional points (Holly Oak, Delaware, Abingdon and Laurel, Maryland), have been established, located as shown between existing repeater points and the terminals.

REPEATERS OR AMPLIFIERS

Each repeater has been especially designed so as to be substantially free from distortion or non-linearity

cies suffer a much greater attenuation during transmission over a cable circuit than do the lower frequencies. Without these equalizers enormous distortion would result.

One new repeater point (Holly Oak) is established in an existing telephone office. At two other points (Abingdon and Laurel) temporary huts have been erected to house the demonstration repeaters.

CARRIER APPARATUS

The carrier system employed is single sideband with the carrier frequency at 40 kilocycles and lower sideband transmission. In order, however, to obtain satisfactory transmission of the very low musical frequencies, what is known as "vestigial" sideband transmission is employed. This means that the unwanted (*i.e.*, upper) sideband is not entirely suppressed in the neighborhood of the carrier but is allowed to pass through the circuit to some extent so as to help out in the preservation of the low notes. This type of transmission circuit requires very careful attention to phase relations in filter design and accurate phase control of the carrier current which is supplied to the demodulator circuit in respect to that supplied to the modulator. As has already been mentioned, this is accomplished by transmitting some of the special control frequency of 20 kilocycles over each transmission line, together with the music band. This transmitted 20 kilocycle control current is used at the receiving end by a frequency doubling device to supply the accurately phased carrier needed for demodulation.

NOISE

As has been referred to earlier, noise entering the transmission system is a limiting factor in determining the extent to which low level sounds can be transmitted and reproduced. Noise can reach a cable circuit in either of two ways. (a) It may enter the cable through the sheath from radio or power fields through which the cable passes, or (b) it may enter the cable at the ends or intermediate points along other circuits in the cable which are operating in a lower frequency range.

So far as (a) is concerned at the frequencies employed and for the transmission levels used, this particular Philadelphia-Washington cable is quiet and was found to require no special arrangements.

With respect to (b) the repeater layout is such that it was not necessary to take special steps, except at Baltimore. Here the volume levels from the north were sufficiently low so that high frequency noises produced in the office as a by-product chiefly of telegraph and switching operations passed into the cable over working circuits and cross-talked into the pairs used for the special broad band transmission. To prevent this the cable north was "isolated" from the office by putting choke coils in every pair in the cable. These choke coils are non-inductive to ordinary telephone or telegraph currents. They are inductive, however, to currents flowing over any of the conductor systems to ground.

LOCAL CIRCUITS

The carrier apparatus is located in the toll terminal offices at Philadelphia and Washington. Small gauge equalized underground cable circuits are used between the Academy of Music and the telephone office in Philadelphia and similarly at Washington between the telephone office and Constitution Hall.

AUXILIARY FEATURES

As has been previously mentioned, spare circuits are available in the cable to substitute in the event of any breakdown of the regularly assigned carrier pairs. Secondary spares of slightly lower frequency range capacity have also been provided in another cable to be available in the remote possibility of something happening to completely disrupt the cable carrying the regular circuits.

SUMMARY

In conclusion, all that need be pointed out is that the system just described is one designed for the reproduction in auditory perspective of symphonic or other music to an audience. Because of its multichannel character and its wide range of frequency and energy capacity, it is not readily adaptable for use in small rooms. While theoretically susceptible of employing any set of transmission channels capable of handling the desired frequency and volume range, it is at least in the present state of the art restricted essentially to wire transmission systems. This restriction arises from three main sources: (1) The ability to free the system against extraneous electrical or noise disturbances which at times so frequently mar radio transmission. (2) The uniformity with which transmission characteristics can be maintained and the relative ease with which the effects of attenuation can be overcome by intermediate repeaters. (3) The fact that under existing statutory regulation of radio it is impossible to secure clear channels of a frequency band requisite for the complete transmission of all the fundamental and overtone frequencies produced throughout the full range of musical instruments and the human voice.

Whether for local or distance use, the easily controlled and very tremendous volume ranges which the apparatus is capable of handling without distortion have placed in the hands of the musical director an implement for tonal effects not hitherto attainable. What the future use of the system in all its parts is likely to be will depend in large measure not only on the extent to which it is desirable to produce perfect music in auditory perspective at a distance remote from the source but likewise on the extent to which musical composers and directors find it effective in producing artistic effects beyond the capacity of the largest orchestras or choruses.

OBITUARY

ARTHUR HOLLICK
1857–1933

DR. (CHARLES) ARTHUR HOLLICK was born in 1857, the son of Frederick and Eleanor Eliza (Bailey) Hollick. He graduated from the Columbia School of Mines, 1879, and from the George Washington University in 1897 with the doctor's degree. He married Adeline Augusta Talkington in 1881. Although scientifically he was a paleobotanist of distinction, he filled many public offices, since he was a man of wide human interests. He was a member of the City of New York Board of Health from 1883 to 1893, a