Audible Frequency Ranges of Music, Speech and Noise *

By W. B. SNOW

This paper describes the use of an electro-acoustic system, transmitting the audible frequency range almost uniformly, in determining by ear the frequency ranges required for faithful reproduction of music, speech, and certain noises.

Sounds were reproduced alternately with and without filters limiting the frequency range transmitted by the electrical circuit. The filter cut-offs producing just noticeable changes in the reproduction were deduced from judgments of listeners as to the presence or absence of filters. It was found that for absolute fidelity all musical instruments except the piano require reproduction of the lowest fundamentals. The frequencies above 5000 cycles were shown to be important, some instruments and particularly noises requiring reproduction to the upper audible limit.

Tests were made in which experienced listeners judged the degradation of "quality" produced by a series of filters. The judgments showed definitely that the quality continues to improve as the frequency range is extended down to 80 or up to 8000 cycles. Although somewhat indefinite on cut-offs outside these limits, they indicated that reproduction of the full audible range was considered most nearly perfect.

ANY sound transmission system, if it is to give faithful reproduction, should transmit all the audible frequencies of a sound in their proper relative intensities. To give acceptable reproduction, it should transmit those frequencies considered most necessary for any particular application. The audible frequency range depends upon physical factors—the frequency-amplitude characteristics of a sound and the hearing characteristics of the average ear—whereas the acceptable frequency range must be determined by judgment when engineering or economic considerations limit transmission. As engineering limitations disappear and practical design becomes more a matter of economics a knowledge of both audible and acceptable limits increases in importance.

The program of listening tests described in this paper was undertaken primarily to establish the audible frequency ranges of the sounds most often encountered in sound reproduction, but some tests bearing on acceptable ranges were included. The sounds were transmitted through an electro-acoustic system equipped with electrical filters by means of which all frequencies above or below any desired cut-off could be suppressed, and observers determined the high and low frequency cut-offs causing just perceptible differences in the transmission. All

* Presented at the Camden mtg. of the Acous. Soc. Amer., May 4–5, 1931. Published in the Jour. Acous. Soc. Amer., July, 1931.

audible frequencies of the sounds were included in the range between the cut-offs thus delineated. Sound sources were: Musical instruments—tympani, bass drum, snare drum, 14″ cymbals, bass viol, 'cello, piano, violin, bass tuba, trombone, French horn, trumpet, bass saxophone, bassoon, bass clarinet, clarinet, oboe, soprano saxophone, flute, and piccolo; male and female speech; noises—footsteps, hand clapping, key jingling. These tests are described in Part I.

Measurements of the relation of reproduced frequency range to the quality of orchestral music, as judged by a number of experienced listeners, are reported in Part II. Tests of this kind must be used in establishing acceptable frequency ranges.

Part I

Apparatus

The reproducing equipment was built by the Bell Telephone Laboratories especially for fundamental studies of speech and music quality. Fig. 1 is a block diagram of the circuits involved in these tests. The

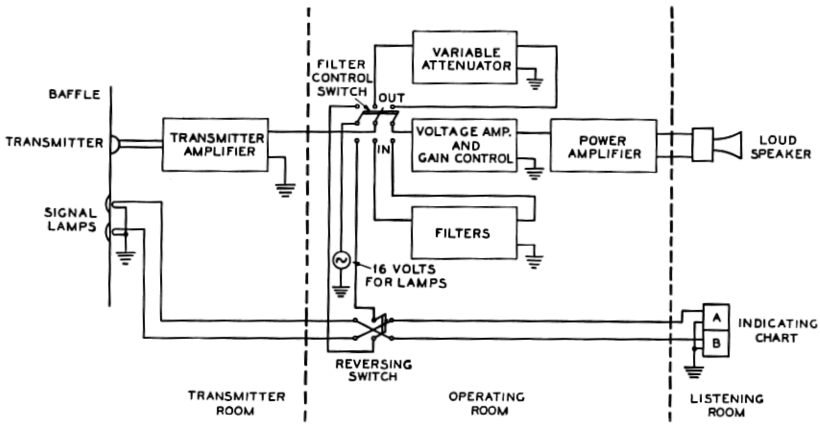

Fig. 1—Schematic circuit diagram of essential apparatus.

electro-dynamic microphone was mounted in a 5′ square baffle placed near the center of a large soundproof room, 29′ × 29′ × 13′ in size, which had a reverberation time of about one second for frequencies between 60 and 4000 cycles. The microphone amplifier, mounted at the rear of the baffle, raised the microphone output to a level that permitted satisfactory switching operations without objectionable surges.

In another room the filters, their switching circuits, and the main amplifiers were set up. The attenuator shown in the "filter-out" circuit was used to compensate for the losses in the transmitted bands of the filters, so that the passed frequencies were reproduced at constant level at all times. Filters available were: high pass 30, 40, 55, 75, 100, 125, 250, 375, 500, 750, 1000, 1500 cycles cut-off frequency; low pass 13,000, 10,500 8500, 7000, 5500, 4500, 3750, 3250, 2850, 2450, 1900, 1500, 1000 and 750 cycles cut-off frequency. All were composite structures giving sharp cut-offs and attenuations of 60 db or more in the attenuated region. Representative attenuation characteristics are shown in Fig. 2.

The loud speaker was mounted in one corner of a third room, of dimensions 18′ × 27′ × 15′, semi-sound proof in construction and exhibiting reverberation characteristics similar to those of the microphone room. To cover the required frequency range, two reproducing

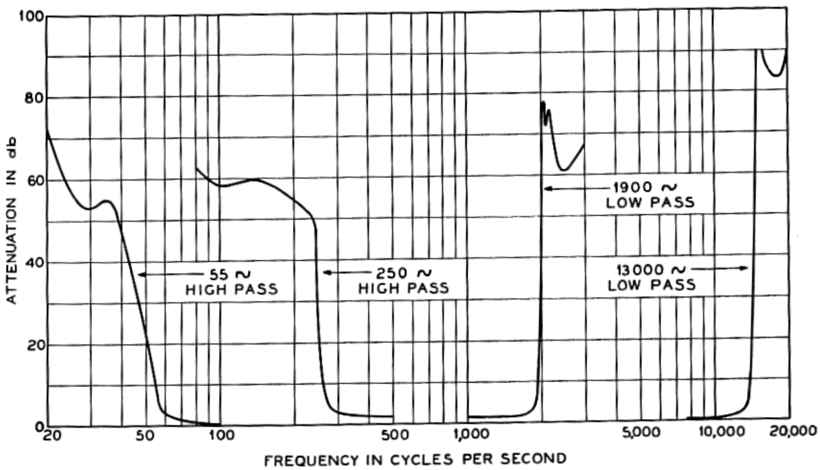

Fig. 2—Attenuation characteristics of four typical filters.

units were employed, one for the four and one-half-octave range below 500 cycles, the other for the five-octave range above this frequency.

The degree of confidence to be placed in the test results depends upon the uniformity with which this range was reproduced. The average overall reproduction-ratio characteristic of the system, shown in Fig. 3, departs from uniformity only about ±2.5 db between 20 and 15,000 cycles. It represents the average for that part of the room which may be called the "listening area," the directional characteristics of the loud speaker not permitting uniform sound pressure throughout the room at very high frequencies. At no point in this area did the measured pressure at any frequency depart more than ±3.5 db from the average curve. One assumption is involved. Because the measurements were made by supplying "warbling" frequencies to the voltage amplifier and measuring the sound pressure in the listening room with the regular system microphone and amplifier, it is necessary to assume that the microphone behaved identically in the microphone room. The two rooms are similar and the assumption was thought justified. The power output capacity of the system was estimated at one-half watt peak sound power with 10 per cent distortion products.

In addition to the speech circuits, Fig. 1 shows an indicating-lamp circuit. Placed before the loud speaker was a small box bearing the letters *A* and *B* on its translucent face. As the filters were thrown in or out the illumination was changed from one letter to the other, the letter corresponding to "filter-in" being determined by the reversing switch. The signal lights beside the microphone were lighted whenever the circuit was closed through. An order-wire circuit (not shown) was used for signalling and intercommunication.

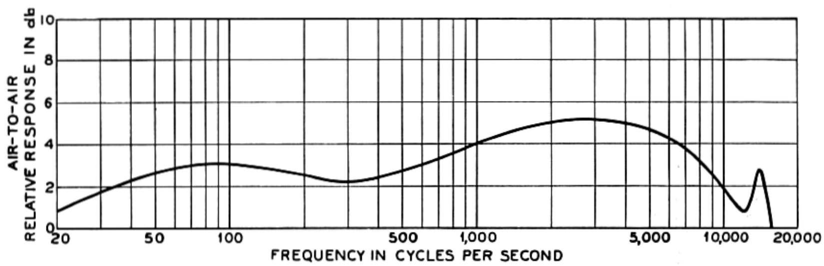

Fig. 3—Reproduction-ratio characteristic of complete system.

Testing Methods

The "A-B Test" method was used in determining the filter cut-offs producing just perceptible changes in the sounds. The observers listened to two conditions, *A* and *B*, one filtered and one unfiltered, and judged which condition was filtered. If the observer obtained a score of 100 per cent correct judgments in a large number of trials the filter was absolutely detectable. A score of 50 per cent correct judgments indicated an undetectable filter, because the observer, if guessing, guessed right and wrong an equal number of times.

Nine members of an articulation testing crew and two young engineers made up the regular observing personnel, though other observers were secured when possible. The actual number participating in the tests varied from nine to fourteen. All were known to have normal hearing, but the predominantly youthful makeup of the crew probably made the crew's average sensitivity for very high frequencies somewhat greater than the general average. The observers were frequently shifted about to insure average results, since the sound field was not absolutely uniform.

Professional musicians were employed in all tests with musical instruments. Usually they were seated as close to the microphone as practicable, and the amplifiers were set so that the sounds were reproduced at natural loudness. The power capacity of the system did not permit this loudness on the drums, cymbals, piano, trumpet, and trombone. For these cases the performers were seated about 10 feet from the microphone and the amplifier gain was reduced the necessary amount. Speakers were seated with their lips 18 inches from the microphone. The keys were shaken about four feet away. Hand-clapping and footsteps were produced at a distance of 15 feet.

The musicians were instructed to play their instruments "loud," as listening tests showed that the widest frequency ranges were thereby produced. Tests were made with the instruments played in their several octave ranges or with their different techniques to insure "boundary" results. In general the performers played repeated three or four note scales, for the differences produced by the boundary filters were too small to be detected regularly except on repeated music not supplied by melodies. However, such a procedure would not be representative for the piano, and regular player rolls were used in testing it. One repeated over and over a 15 second passage emphasizing the notes of fundamentals 32 to 800 cycles, the second similarly emphasized notes of fundamentals 200 to 3500 cycles, while the third was a march covering the range 40 to 1500 cycles.

Before the regular crew started work on each sound the engineers in charge listened to the reproduction and picked out the playing techniques that promised the widest frequency ranges. Tests always started with a filter giving 90–100 per cent correct judgments and continued through successive cut-offs until the 50 per cent cut-off was reached. Throughout both the preliminary and regular tests the observers made notes relative to quality changes produced by the filters, and noises produced by the instruments. With the performers and observers in readiness for an actual test the procedure was as follows: The filter operator threw the main switch from neutral to the position lighting the "A" lamp, which might be "filter-in" or "filter-out" as he chose. The performer, seeing his signal lamp light, then played his instrument for a period of 15 to 20 seconds as the operator switched "A-B-A-B-neutral." Switching to neutral stopped the musician by extinguishing his signal light, and gave the observers an opportunity to check on their recording blanks the condition they believed to be filtered. The process was repeated five times with a random order of correspondence between A or B and "filter-in." When necessary a filter was retested until practice effects were eliminated. Since there were never less than nine observers, and each had at least six trials on each filter, the minimum number of observations used in computing the percentage of correct judgments on any filter cut-off was 54. Several times check tests were made in which the lights were changed, but no filter was inserted. The average scores on these tests always were within the limit 50 ± 4 per cent.

Data

The filter cut-offs producing just noticeable effects upon the sounds were not sharply defined. For every sound there was, between the cut-off recognized every time and the cut-off never recognized, a certain region of appreciable width where the percentage of correct judgments decreased from 100 per cent to 50 per cent. If this percentage is plotted against cut-off frequency a curve such as is shown in Fig. 4

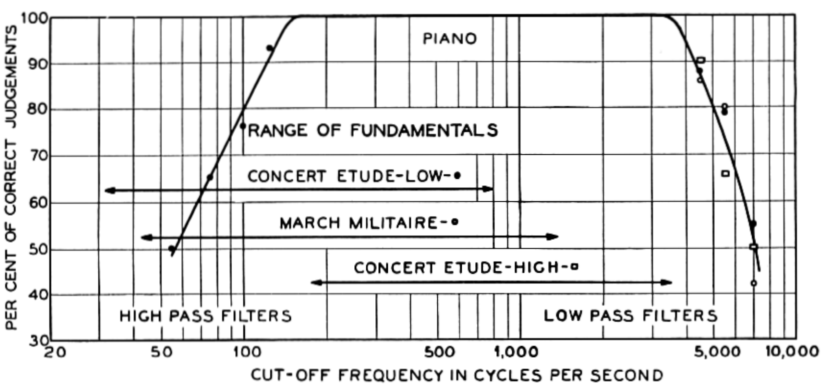

Fig. 4—Number of times filter condition was correctly perceived as function of cut-off frequency—piano.

results. Curves of this kind proved useful for interpolation purposes, but their contours were felt to be too dependent upon the individual peculiarities of observers and players to be of general significance. No close correlation existed between the importance of any frequency range and the contours of the curves, for the differences caused by the filters that were recognizable in less than 80 per cent of the tests were very small. In addition, some observers consider that elimination of high frequencies improves the reproduction of certain musical sounds by removing accompanying noises. Therefore it was decided that the useful information from the data could best be presented by straight lines.

The audible frequency ranges of all the sounds tested have been plotted in this way in Fig. 5. The end points for these lines have been taken where the correct judgments amounted to 60 per cent. In addition, the frequencies where 80 per cent correct judgments were obtained have been marked. The region between the 80 per cent marks is the most significant—frequencies above and below would probably not be heard at auditorium distances or with other instruments playing. There were certain sounds that apparently extended to the highest audible frequencies as judged by the ease with which the highest filter—

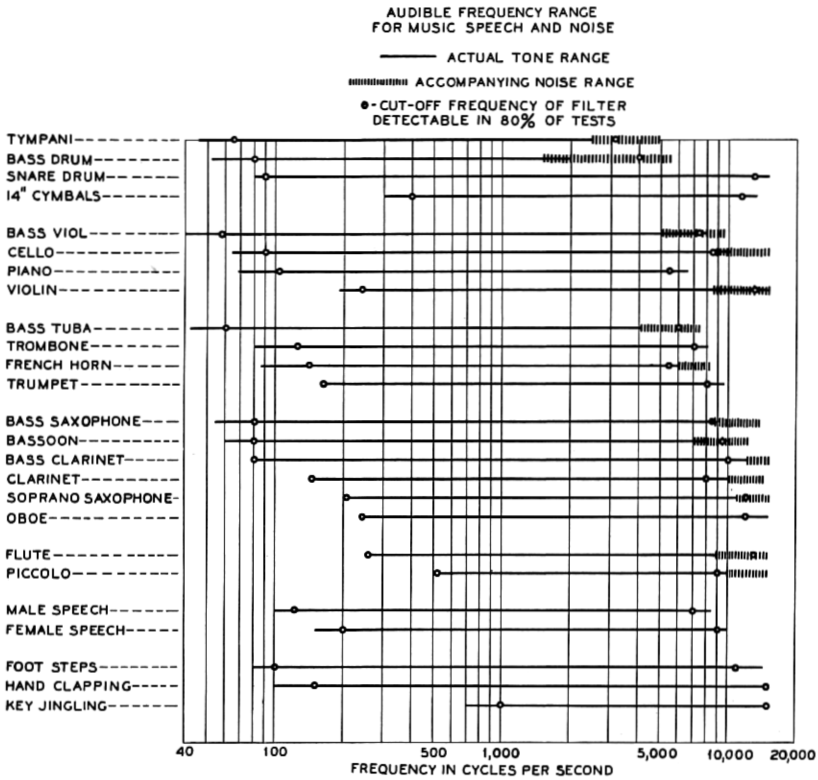

Fig. 5—Audible frequency ranges.

13,000 cycles cut-off—was detected. In these cases the lines have been arbitrarily stopped at 15,000 cycles.

With most instruments it was noticed that the actual musical sounds were accompanied by other sounds such as key clicks, lip noises, "buzz" of reeds, and hissing of air. The observers tried to distinguish between the frequency ranges carrying the two classes of sounds, and their judgments are summarized by the treatment of the lines of Fig. 5. The heavy portions indicate the frequency ranges thought to convey the "tone quality" of the instruments, and the short vertical lines define the ranges of noise. In some cases noise and tone seemed inseparably blended.

The qualitative observations made by the observers are summarized in the notes below, in which "L. F." means "lowest fundamentals."

Tympani—No important frequencies below 65 cycles (drum tuned to 96 cycles). Actual tone range ends around 2000 cycles. Prominent drum rattle and beating noises to around 5000 cycles.

Bass Drum—No important frequencies below 70 cycles. Actual tone range ends around 1000 cycles. Prominent drum rattle and beating noises to around 5000 cycles.

Snare Drum—No important frequencies below 100 cycles. Actual tone consists of rattle extending to very high frequencies.

14″ Cymbals—No important frequencies below 350 cycles. Low frequencies prominent when one cymbal is struck with a hard stick. High frequencies prominent when two cymbals are clashed together.

Bass Viol—L. F. fairly important, slightly more on plucked than on bowed notes. Considerable bowing noise.

Cello—L. F. fairly important. Tone very rich in harmonics. Moderate bowing noise.

Piano—L. F. unimportant for first octave. 100 cycle high pass filter only slightly noticeable. Upper notes practically pure tones.

Violin—L. F. important. Tone rich in harmonics. Noises and tone blended.

Bass Tuba—L. F. fairly important. "Pedal" notes—fundamentals around 20 cycles—contain fewer very low frequencies than regular notes. Moderate blowing and key noises.

Trombone—L. F. not very important below 130 cycles. Middle register has greatest harmonic content. Inappreciable noise.

French Horn—L. F. unimportant below 130 cycles. Middle register has most volume and harmonics. High register gives rather pure tones. Harmonics least prominent of any instrument tested.

Trumpet—L. F. fairly important. Lowest register has greatest high frequency "blatt." Tones purer at higher pitches. Inappreciable noise.

Bass Saxophone—L. F. not very important below 90 cycles. Highest register rather unmusical and unpleasant. Considerable blowing and key noise.

Bassoon—L. F. fairly important. Prominent reed noise on lower register. Moderate key slap.

Bass Clarinet—L. F. very important. Tone goes to very high frequencies on upper register. Prominent reed noise on lower register becoming blended with tone on upper register.

Clarinet—L. F. very important. Medium range has largest harmonic content. Highest range gives much purer tones. Moderate blowing and reed noises at very high frequencies.

Soprano Saxophone—L. F. very important. Powerful harmonics making very harsh tone. Moderate reed noise above 10,000 cycles, less than that of clarinets.

Oboe—L. F. important. Most "reedy" tone of all tested. Tone extremely rich in harmonics of high order, especially middle register. Noises blended with tone.

Flute—L. F. very important. Middle register has most harmonics. Highest register produces almost pure tones. Much blowing and mechanism noise on highest register.

Piccolo—L. F. very important. Middle range most musical and free from noise. Highest few notes are very powerful but are practically pure tones. Much blowing noise and rumble on all registers.

Footsteps—No important frequencies below 100 cycles. High frequencies up to about 10,000 or 12,000 cycles required.

Handclapping—No important frequencies below 150 cycles, but requires the entire audible range on the high frequency end. Sounds fairly natural with 8500 cycle cut-off.

Key jingling—bunch of 22 keys shaken on 4″ wire loop—No important frequencies below 500 cycles but requires entire audible range on the high frequency end. Tone very unnatural with 8500 cycle cut-off.

It is felt that the caliber of the playing was such as to render the comments and measured frequency ranges generally applicable. These ranges probably represent extreme conditions, for the observers were in effect situated unusually close to the instruments, they were listening under most favorable conditions, and they had only to pick out a particular distortion.

The piano was the only instrument which did not require the reproduction of its lowest fundamentals for perfect fidelity. Therefore transmission of 40 cycles—the lowest note of the bass viol—was required, and this was found to be ample for the percussion instruments. However, as the 80 per cent marks indicate, little was lost when frequencies below 60 cycles were not reproduced.

Many of the instruments produced noises that extended to high frequencies, but only the oboe, violin, and snare drum were thought to extend their tone ranges to the upper audible limit. The action of bows on the strings and the clatter of reeds in the reed instruments produced very prominent noises of high frequency. When the lips were used as reeds the noises were much less prominent. The noises indicated for the flute and piccolo were produced by the impact of the air from the lips against the embouchure opening. As a group the lipped instruments produced only moderately high frequencies; the other groups all had some instruments producing frequencies extending to the upper audible limit. An upper cut-off of 10,000 cycles did not affect the tone of most of the instruments to a marked extent, but every instrument except the bass drum and tympani was affected by the 5000 cycle cut-off. A frequency range of 100 to 10,000 cycles was shown to be entirely satisfactory for speech.

Between the 80 per cent marks the bass viol required the greatest range—7 octaves—and the piccolo required the smallest range—4 octaves.

Noises in particular were characterized by high frequencies. Hand clapping and key jingling were both found to be very definitely changed by the 13,000 cycle filter, and informal listening tests on several other noises indicated that high frequencies were very prominent. Probably many noises also contain important frequencies below 100 cycles and transmission of the entire audible range would seem much more important for noise reproduction than for reproduction of musical sounds.

Part II

The measurements of the quality changes produced by the filters were made using the same apparatus but a different testing technique. The 18 piece orchestra furnishing the music was made up as follows:

3 first violins, 1 second violin, 1 viola, 1 'cello, 1 string bass, 1 flute, 1 oboe, 2 clarinets, 1 bassoon, 2 French horns, 2 trumpets, 1 trombone, 1 drummer. The players were seated in concert arrangement with the violins about 8′ from the microphone. Ten engineers experienced in quality judgments acted as observers. In these tests the filter conditions were always presented as "B" and the observers were asked to rate the quality of the "B" condition numerically, considering the "A" condition to possess a quality of 1.0. The ratings could be either less than 1.0, indicating a degradation, or greater than 1.0, indicating an improvement. Conditions were switched A-B-A-B—, continuing until all observers had obtained a judgment, but the filters were presented in

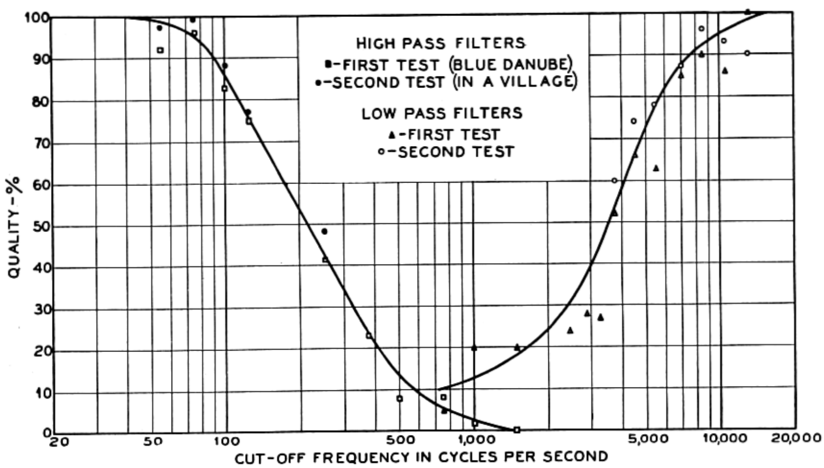

Fig. 6—Quality of orchestral music as function of cut-off frequency.

perfectly random order. Therefore the observers were never informed as to what filter was being tested; they only knew that "A" represented a quality of 1.0 and "B" a condition to judge.

The orchestra played the Strauss waltz, "The Beautiful Blue Danube," for the first test. It was orchestrated so that most of the instruments played most of the time. All filters except 30 and 40 high pass were presented to the observers. From the results a list of filters which all observers had rated as better than 0.5 was compiled for presentation during a second test. This time the music was "In The Village," a composition of Godard. It was a selection in which many instruments had solo parts and in which therefore the character of the music changed rapidly.

The average ratings for both runs are plotted in Fig. 6. The two sets of data agree reasonably well except at the extreme ends where differences are small and the judgments are greatly affected by particular instruments. Clearly the quality rises rapidly as the cut-off is extended upwards to 8000 cycles, or downward to 80 cycles, but outside these limits the results are inconclusive. Out of 370 ratings recorded, only a scattered 13 were greater than 1.0. In general, therefore, it must be concluded that reproduction of the full audible range was preferred.

The curves of Fig. 6 do not define acceptable frequency ranges directly, but the method with slight changes would give them. The observers would be instructed to judge whether for any particular application the range being heard would be satisfactory. However, these curves, coupled with the general experience of engineers and musicians should aid in determining acceptable ranges where direct tests are impracticable.

Conclusion

The author is not familiar with any published results of comprehensive listening tests that can be compared directly to these data. However, the audible ranges here presented have been compared with physical measurements [1] of peak sound output of a number of the instruments. The physical measurements give the peak amplitudes in octave ranges below 500 cycles, and in half octave ranges above this point, whereas interpolation between these limits was possible in selecting the audible ranges. On the other hand, auditory masking must play a part in determining the audible cut-off points. Considering these limitations to comparison, the two sets of data are consistent on every instrument tested in common.

The more important results of the tests are considered to be as follows:

1. The piano was alone in producing tones with inaudible fundamentals.

2. Audible frequencies down to 40 cycles were produced by the musical instruments, but reproduction only to 60 cycles was considered almost as satisfactory.

3. It was found that transmission of the highest audible frequencies was needed for perfect reproduction of musical instruments, mainly because of the noises accompanying the musical tones. A 10,000 cycle upper cut-off had slight effect upon the tone quality of most instruments, but a 5000 cycle cut-off had an appreciable effect upon all except the large drums.

[1] "Absolute Amplitudes and Spectra of Certain Musical Instruments and Orchestras" by L. J. Sivian, H. K. Dunn and S. D. White, *Jour. Acous. Soc. of America*, January, 1931.

4. The quality of reproduction of orchestral music continued to improve materially as the lower cut-off was extended to about 80 cycles and the upper cut-off to about 8000 cycles. Reproduction of the full audible range was preferred to any limitation of band width.

5. Noises required reproduction of the highest audible frequencies. A 10,000 cycle cut-off caused appreciable reduction of naturalness on common noises. It was felt that this cut-off probably would never preclude recognition of a noise.

The results seem to necessitate no radical revision of the qualitative ideas entertained by many acoustical engineers for some years, their value lying rather in the quantitative corroboration they supply.