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FREQUENCY RANGE AND POWER CONSIDERATIONS IN MUSIC REPRODUCTION

By Technical Service Department » » » » Jensen Manufacturing Company

THERE can be very little doubt that we stand on the threshold of a new era in radio transmission and sound reproduction. We can confidently expect that these facilities can, and shortly will, bring into American homes greatly improved, higher quality services. How much improvement we can expect over previous services and the degree to which potential improvements can actually be utilized, are questions which remain to be answered.

Both FM Broadcasting and Television are today serving extremely small audiences on a limited basis. Expansion of both of these services has been blocked until the end of the war when production of the necessary transmitters and receivers can be resumed. In the meantime, the American Public awaits developments (sometimes extravagantly described), and the executive heads of the Radio Industry, with their engineering and sales staffs, are studying the facts and planning for the resumption of civilian production.

Among the basic questions which must be answered are these: What frequency range is needed if we are to take advantage of improvements in broadcasting made possible by the FM system of transmission? What limitations on frequency range may be imposed by the hearing ability of the listener and the usual noise levels which surround him? What are the principal design and cost factors which must be considered? This Monograph is intended to assist in arriving at the answers to these highly-important and timely questions.

Economics of Wide-Range Reproduction

The reproduction of music is perhaps the most critical application of loud speakers because of the wide range of frequencies and powers covered by the various instruments, the need for low distortion, and the importance of spatial distribution of the reproduced sound. Yet it is a matter of record that a fairly high degree of listener satisfaction is obtained from reproducing systems which fall far short of the theoretical ideal in all of these respects.

As improvements in the overall system performance become technically possible, the question arises as to the lengths to which it is worth while to go to take advantage of these advances, and the nature of the improvement which can be effected in practical systems under average conditions of use. These questions are particularly important at this time, because frequency modulation transmission facilities will undoubtedly be greatly expanded, thus providing a widespread source of potential high quality program material.

Our problem is to appraise the complete transmission system up to and including the ear of the listener so that we can specify a sound reproducing system which will transmit the full *useful* range of frequencies and powers, and yet not suffer the economic burden imposed by the cost of an over-range design. Some idea of the importance of a fairly accurate estimate of the required frequency range may be gathered from Fig. 1, which shows in a general way the extent to which reproducer costs increase as the upper limiting frequency is moved out beyond 5,000 to 6,000 cycles (5 to 6 kc). Above these frequencies, it becomes imperative to subdivide the range and to use a number of repro-

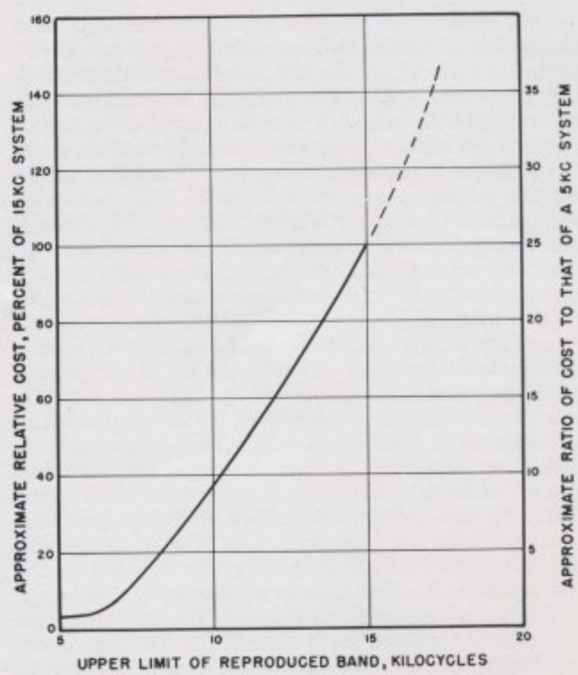

Fig. 1. Approximate Relative Costs of Electroacoustic and Associated Components of a Sound Reproducing System at Various Upper Limiting Frequencies.

ducing elements with their associated frequency-dividing networks in order to attain the required efficiency and best possible spatial distribution of sound over the prescribed total frequency spectrum. Actually, of course, the cost curve should be a stepped curve with a vertical increase for each additional reproducer unit with its network, but since the choice of the dividing frequency and other factors vary considerably in commercial applications, only the trend of the average has been indicated. Obviously, the choice of the lower frequency limit will also affect the cost, as will the power rating of the reproducer. The cost estimates assume a suitable power rating for home reproduction levels with a low cut-off frequency known to be generally acceptable.

Perceived Frequency Ranges

We are not primarily concerned with the question of reproducer costs in this study. The cost element has been mentioned early in order to show the steep upward trend with increased frequency range and to permit the later appraisal of the economic effects of compromises.

What range of frequencies the listener can perceive depends, first of all, on his innate hearing ability, secondly on the average level and spectral composition of the sound and lastly, and of great importance in the determination of the final result, the level and character of the ambient noise background in which he is immersed.

All of these factors are variables. First of all, hearing ability differs widely in the population. The extreme range of frequencies which can be perceived by an individual with acute hearing *when the sounds are at near-pain intensity* is from about 16 to 22,000 cycles. As the intensity is decreased, the perceivable frequency range is shortened at both ends. Only about 5% of the population is able to perceive such a wide range of frequencies, even at the highest sound intensities. The median range for the population is from 20 to 15,000 cycles per second at an intensity level of 120 db. For the 5% with the poorest hearing, the range is less than 25 to 7,000 cycles. All of these figures are at the threshold of pain, and do not represent the situation at the usual intensity levels where the perceived frequency range is much less. The complete picture of the statistical hearing contours for these groups of the population is given in Fig. 2, which is taken from an analysis by Fletcher[1] of the hearing records of more than 500,000 people[2]. This large sample, representative of a typical population, included people of both sexes and all ages, and thus takes into account recognized trends with age and real differences in the hearing loss of men and women. We are thus able to define statistically with considerable assurance, the hearing ability of an *average listener*, and of a *critical listener*. We can then use these two contours as fundamental data in determining the perceived frequency range, subject to the masking effects of various noise levels.

Noise is another highly variable element. Noise levels are higher in the summertime when windows

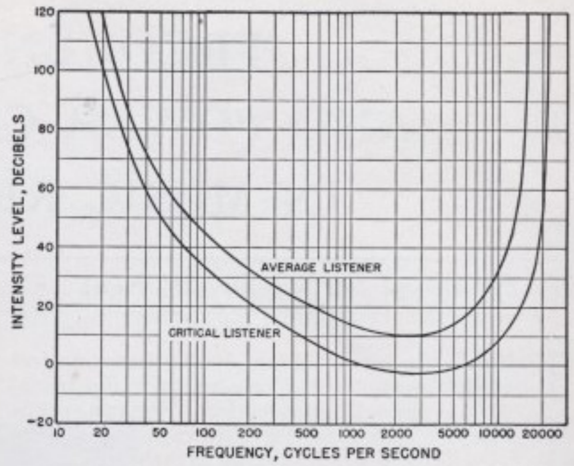

Fig. 2. Hearing Contours for Average (Median Population) and Critical (5% Most Acute) Listeners in the Absence of Noise.

are open and traffic is somewhat heavier than in winter. Noise depends on location, being higher in level in heavy urban traffic areas than in quiet suburban districts. It depends also on the number of people in the room, on the proximity of mechanical equipment, and is quite variable from instant to instant. Noise acts as though it deafened the individual situated within it. For any particular level and spectral distribution of noise, there results a masking contour which defines the intensity level of a single frequency tone which will be audible to the listener, provided his normal threshold (in the absence of noise) is equal to or lower than the masking contour.

Seacord[3] has published the results of about 2,200 measurements of room noise which indicate that the annual average residential noise level is 43 db. Only 5% of the residences had a noise level of 33 db or less, which checks closely with previously reported measurements in very quiet residences. This gives us two significant room noise levels for which the corresponding masking levels may be obtained by assigning typical spectral distribution[4] to the noise, then calculating the masking contours[5] from these spectra. These contours are shown in Fig. 3.

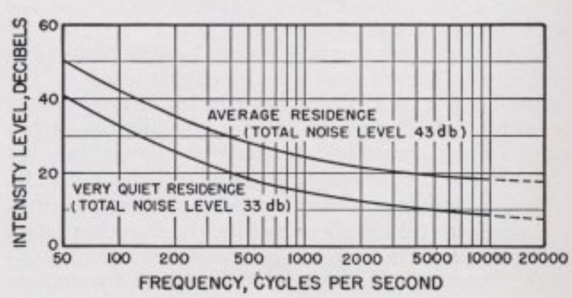

Fig. 3. Masking Level Contours for Noise in Average and Very Quiet Residences.

We can now combine the normal hearing contours with the masking contours in a variety of ways, if we choose, in order to determine the ability of a statistical listener to hear in the presence of representative noise conditions. For our purposes, we are interested in the average case which represents a very large segment of the population, and this results from pairing average hearing acuity with the masking contour corresponding to average residential noise. Although it probably involves much less than 1% of the population, we should also examine the case in which the combination of hearing acuity and masking contour yield the widest possible perceived frequency range. We may take the acuity of our previously defined critical listener and pair it with the masking for 33 db noise for this case. The contours for these two cases are shown in Figs. 4 and 5.

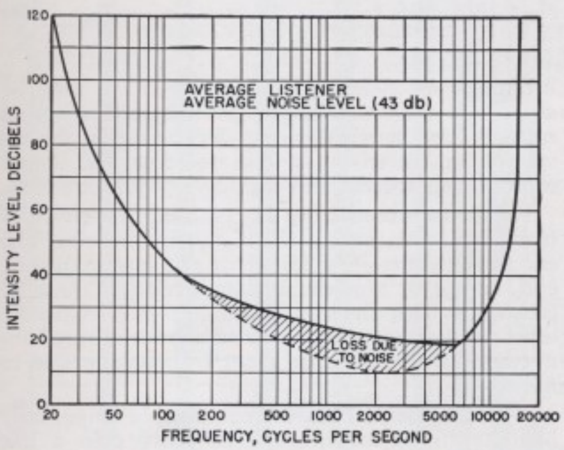

Fig. 4. Effective Hearing Contour for Average Listener Situated in Average Noise.

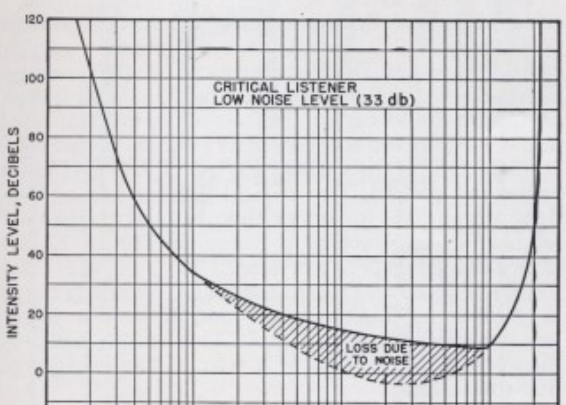

Fig. 5. Effective Hearing Contour for Critical Listener in Low Noise Level.

The Nature of Music

To describe music in physical terms is exceedingly difficult. In symphony orchestra music, we know from tradition the kind and probable number of instruments which will be played, but the compositions and conducting technique introduce seemingly almost unlimited variables in frequency and intensity. The only possible approach to a solution is by sampling and statistical analysis of the data. Sivian, Dunn and White[6] have taken such samples for a small number of orchestras playing a variety of different compositions. By use of band filters and a counter system employing gas tubes arranged to fire at intervals over the range of levels involved, they obtained the distribution in sound pressure level for frequency bands covering the entire musical spectrum.

After introducing suitable corrections, Fletcher[1] has arrived at the maximum root-mean-square values in ¼-second intervals in critical frequency bands at a 20-foot distance for symphony orchestra music, based on the data just referred to. These maximum r. m. s. levels are the *effective* values of the *peak intensities** as perceived by the ear. Now if the total reproduction level is such that the maximum r. m. s. intensity level in any particular frequency region is just equal to the masking level, then the components of the music in that region will never be heard. Furthermore, since the peak intensities occur relatively infrequently, the average level will be considerably below the masking level. For this reason it appears that the use of average or statistically most probable intensity levels should provide a more representative result in determining the perceivable frequency range.

The *most probable levels* in critical frequency bands are substantially lower than the maximum levels. The values which we have calculated[7] from the original data[6] are shown in Fig. 6 along with Fletcher's maximum values. At 300 cycles per second, the most probable intensity is about 7 db below the maximum, while for most of the frequency range up to 5,000 cycles per second, it averages about 12 db below the maximum. Above this point, the divergence is greater, the most probable value being 28 db below the maximum at 15,000 cycles per second.

Now if we adopt the most probable intensity level curve as the spectral distribution which is most representative of the average acoustic intensity levels encountered in listening to symphony orchestra music, we are in a position to determine the perceived frequency range on a statistical basis, using the effective hearing contours for the average listener and the "critical listener" shown in Figs. 4 and 5.

The position of the most probable intensity level curve is determined by the total level of reproduction. In Fig. 6 it is shown for concert hall levels at a distance of 20 feet from the orchestra. This is for a long average total level of 88 db. It has been

* Defined as the intensity level which is exceeded only 5% of the time in the particular critical frequency band.

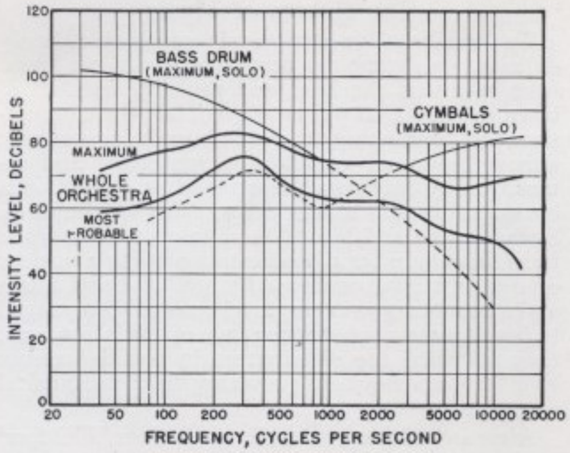

Fig. 6. Maximum and Most Probable Levels in Critical Frequency Bands for Symphony Orchestra Music. (20 *ft. Distance,* ¼*-second intervals.*)

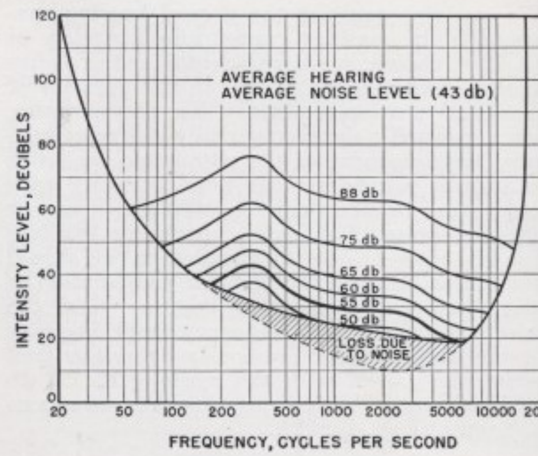

Fig. 7. Perceivable Frequency Ranges at Various Reproduction Levels for the Average Listener.

estimated from Seacord's data[3] that the average total level for home radio reproduction is about 55 db at probable listening positions[7]. Therefore, assuming an ideal transmitting and reproducing system, we may determine the perceivable frequency limits within the home under average conditions by lowering the curve 33 db and noting the frequencies at which the hearing threshold curve is intersected. The manner in which the perceivable range varies with the level of reproduction can be studied similarly by raising or lowering the curve.

This process is illustrated in Fig. 7 for the average listener case. For reproduction levels down to 60 db, it will be seen that the limiting frequencies are determined purely by the normal hearing contour. At average radio level (55 db), masking due to noise is already appreciable and limits the perceivable range to 175 to 5,800 cycles per second; as the level is decreased further, the effect of masking rises very rapidly. At a reproduction level of 50 db, only 5 db below the assumed average radio level, the frequency range has been restricted to 220 to 3,300 cycles per second, and midrange masking has set in between 700 and 1,200 cycles per second. Many radio receivers are operating at such low levels. It is interesting to note that, in the complete absence of noise, the perceivable frequency range would be from about 200 to 5,000 cycles per second at the same reproduction level. A reproduction level of 50 db seems to be about the lowest for which the average listener could claim any valid interest in the quality of reproduction. In this connection, it must be remembered that this analysis is based on an *ideal transmission and receiving system which is capable of reproducing an unlimited band of frequencies with complete uniformity*. We know that the great majority of existing AM radio receivers have a nonuniform response characteristic and reproduce a limited frequency range, determined principally by the r.f. selective circuits. Thus for actual radio listening, the perceived frequency range may be much less than the ranges given here, the actual range in any particular case depending on the response characteristic of the receiver and sound reproducing system and the level of reproduction.

It will be noted from Fig. 7 that the effect of masking is greatest for the higher frequencies. The ear is the controlling factor at the low frequency end, except at abnormally low levels. At the high frequency end, the ear determines the frequency limit at above-average levels, while for lower-than-average levels the limit is set by masking due to noise.

By the same process, the perceivable ranges may be determined for the critical listener in a low noise level. The results for both types of listeners are summarized in chart form in Fig. 8 for the usual intensity ranges encountered in home listening.

It is immediately apparent that under the assumed ideal conditions of perfect transmission into the home, the listener is able to perceive only a restricted range of frequencies. For the average listener (at average reproduction level) the range of 175 to 5,800 cycles per second represents only about 62% of the total number of octaves assumed transmitted in the whole range of 40 to 15,000 cycles per second. The critical listener has an evident advantage, for under the assumed conditions, he is able to perceive a range of 120 to 12,000 cycles which represents about 81% of the total number of octaves transmitted. The frequency range is greater for higher levels and lesser for lower levels as indicated in Fig. 8. The broken bars indicate the obliteration of a part of the mid-range due to masking.

Difference Limens

The foregoing analysis gives us a picture of the perceivable frequency ranges for a perfect transmission system operating at various reproduction levels in the home. It shows us statistically what

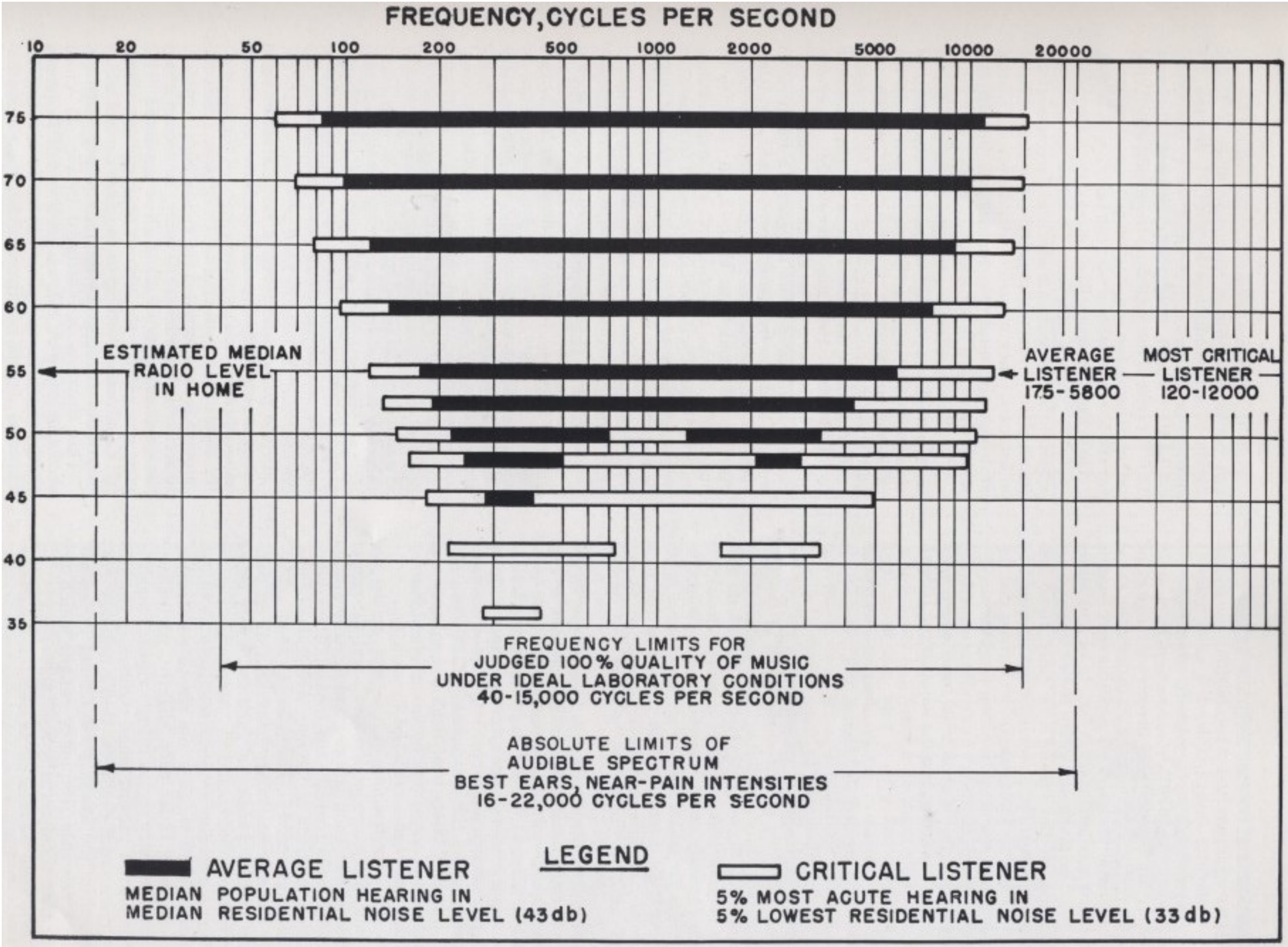

Fig. 8. Statistical Perceived Frequency Ranges as Limited by Hearing and Noise. Based on Most Probable Levels in Critical Frequency Bands of Symphony Orchestra Music.

the situation is at average level and at any other level. If we are interested in establishing the widest useful frequency ranges, then the conditions at higher-than-average levels must be examined.

Fig. 8 shows that at a reproduction level of 75 db, the critical listener may perceive a range of 60 to 15,000 cycles. For the average listener the range is 85 to 11,000 cycles. This reproduction level is 13 db below assumed concert hall level and represents about the maximum likely to be employed, on the average, in the home. Now since these frequencies approach ideal requirements, it would be useful to know to what extent the listener can detect changes in the upper limiting frequency.

Gannett and Kerney[8] have determined the minimum perceptible change in band width with direct comparison between the bands being judged. Their tests were made on a variety of musical program material and with a very low noise level (30 db). An average of sixteen observers, who were engineers accustomed to judging program quality, were used for the tests. The *difference limen* was taken as the difference in band width (i.e., difference in high frequency cut-off) when 75% of the observers correctly identified the wider of the two bands presented for comparison. It is reasoned that the difference limen is equivalent to (1) *the difference in band width which is actually detectable to half the observers* or (2) *the threshold difference in band width for which there is an even chance of its discernment by a listener.* The sensation due to a change of one difference limen is defined as one *liminal unit,* for which we propose the symbol "LIM."

The result of these tests may be expressed in the family of transmission characteristics given in Fig. 9*, in which the cut-off frequencies differ by steps of 1 LIM. Thus 11,000 cycles per second is 1 LIM down from the full musical spectrum band of 15,000 cycles per second; 8,000 cps. is 2 LIM down from full band, or 1 LIM down from 11,000 cps., etc. The 1 and 2 LIM steps at the low frequency end are a matter of conjecture by Gannett and Kerney and have not been established by test.

The previous training of the test crews, the relatively high reproduction level, and the use of repeated direct comparisons, undoubtedly results in liminal values which are too small for home listening conditions or for commercial demonstrations of radio receivers. The average listener seldom if ever has an opportunity to make a direct comparison involving *change of band width only* under properly controlled conditions. Moreover, it is not possible to appraise properly relatively small differences in band width if the response characteristics otherwise differ even slightly, particularly near the frequency region being judged. This difficulty is always present when comparing two different commercial products. Under ordinary conditions, then, the use of these liminal values will yield perceivable frequency ranges which are greater than those actually realizable.

*These are for music. One liminal unit for speech is equal to about two liminal units for music.

Now if, as shown previously, the critical listener can perceive an upper frequency limit of 15,000 cycles at a reproduction level of 75 db, the frequency range can be reduced to 11,000 cycles (-1 LIM) without detectable difference. Therefore 11,000 cycles is the maximum frequency which need be reproduced for the critical listener. Similarly, for the average listener who can perceive an 11,000-cycle upper frequency limit, a maximum frequency of 8,000 cycles is sufficient. These frequency limits appear to be the maximum which can be economically justified for home reproduction for these classes of listeners. They represent frequencies not merely at which the return is diminishing, but beyond which the return is substantially zero.

The size of the frequency intervals for one liminal unit provides a useful measure of the effect of changes in the upper frequency limit. Fig. 10 enables the frequency corresponding to one liminal unit plus or minus to be determined for any reference frequency. Suppose that a system transmits to 9,000 cycles. How much would this upper frequency limit have to be extended to make a perceptible difference? From the plus one limen curve we find that the frequency corresponding to 9,000 cycles is 12,200 cycles. Thus the frequency range must be extended to at least 12,200 cycles to be noticeable. Again, suppose that the system transmits to 10,000 cycles and it is desired to reduce the frequency range as much as possible without introducing more than a just perceptible change. From the minus one limen curve, we find the frequency corresponding to 10,000 cycles to be 7,400 cycles.

Nature of the Response Characteristic

If we wish to reproduce music with absolute fidelity, not only must the frequency range be adequate as discussed previously, but also the transmission characteristic must be uniform over the entire frequency range. Such absolute fidelity is, of course, not realizable except under laboratory conditions with highly special equipment. It is possible, however, to approach uniformity sufficiently closely in a well designed sound reproducing system. To do this over extreme frequency ranges requires a multiple speaker system in which, among other things, careful attention is given to the problem of attaining wide spatial distribution of radiation at the high frequencies.

In the past, radio receiver manufacturers have felt it desirable to use loud speakers which contributed to the apparent sensitivity of the set, with the result that loud speaker designs in which the response is emphasized in the middle high frequency to attain high loudness efficiency, have constituted the great majority of all of those produced. This may account for the almost universal preference for an advanced setting of the tone control which drastically reduces the high frequency response.

This situation is illustrated in Fig. 11 which shows in curve A the loudness versus frequency characteristic for symphony orchestra music (after Fletcher). It will be observed that the ear is stim-

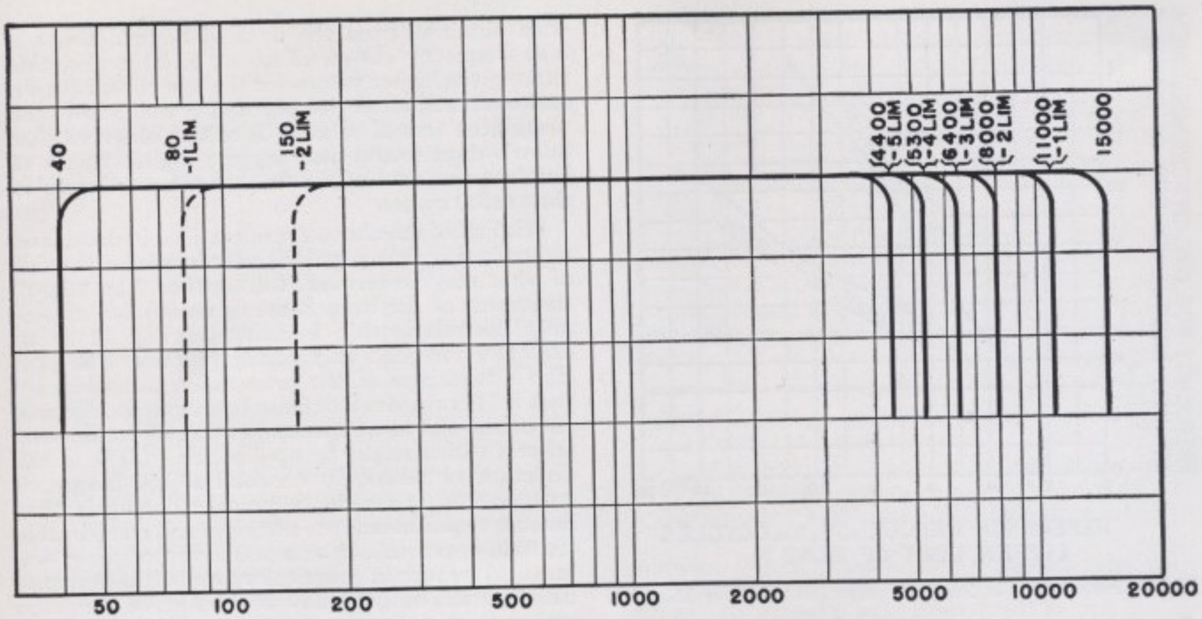

Fig. 9. Transmission Bands Differing by One Liminal Unit (LIM) for Music. After Gannett and Kerney. (Note: Frequencies for 1 and 2 LIM at low frequency end of band are conjectural and have not been established by tests.)

ulated most in the 2,000 to 3,000 cycle region despite the fact that the maximum and most probable intensity levels are highest in the 200 to 400 cycle region as shown in Fig. 6. If such music is reproduced over a loud speaker in which the middle high frequency response has been accentuated, the listener will experience loudness sensations something like curve B. Excessive stimulation in the middle high frequency region seems to be universally objectionable to most listeners. The irritation of such excess stimulation can be reduced by lowering the response in this frequency region. With the usual type of high frequency tone control, this is accompanied by excessive shortening of the high frequency range, with a final result which is approximated in curve C. It should be remembered that these are loudness curves and not conventional response curves. One is led to conclude that listeners predominantly prefer the loss of the upper frequency region to excessive middle high frequency response. *This is no indication that high frequency components at the top of the range are not wanted.* There is considerable evidence that most listeners prefer a wide frequency range to a restricted range when listening to high quality program material over a system with a relatively uniform response characteristic and proper spatial distribution of the high frequency sound radiation.

Low Frequency Limit; Balance

Thus far we have been mainly concerned with the total reproduction band width in order to establish the necessary high frequency limits. It has long been recognized, however, that the high- and low-frequency cut-offs are related to each other for limited fidelity reproduction (i.e., when the complete theoretical music spectrum is not reproduced) if the listener is to gain the most pleasing impression of appropriate aural balance between the high and low frequency components. Thus, if the upper cut-off is at 5,000 cycles per second, it has previously been considered that the lower cut-off should be somewhere between 100 and 130 cycles per second. If the upper cut-off were raised to 7,000 cycles per second, according to the established view, the lower cut-off should be at about 70 to 90 cycles per second. A relationship of this type corresponds to a constant product of the cut-off frequencies and different authorities have given values for the constant ranging from 500,000 to 640,000.*

There is no doubt that the constant product relationship with constants of 500,000 to 640,000 will give excellent high-quality reproduction, completely satisfactory to most listeners, when applied to high-fidelity systems. However, we need to reexamine this concept, particularly in the light of the work recently published by Gannett and Kerney[8] on frequency difference limens, in order to establish what is perhaps the whole permissible range of values and to provide a basis for good engineering practice taking into account the economic factor. Extensions of the low frequency range downward

*Values as low as 400,000 are to be found in earlier literature.

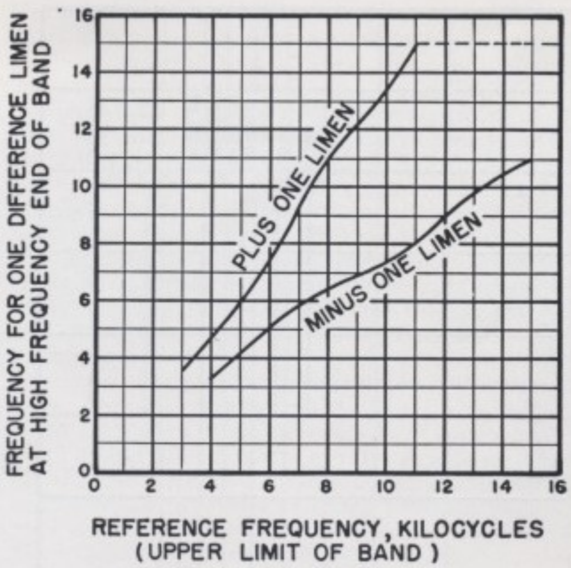

Fig. 10. Frequencies for One Difference Limen Plus or Minus at High Frequency End of Band.

involve increasing cost and bulk, neither of which ought to be carried any further than is necessary to insure a completely satisfactory result.

A system reproducing the entire musical range from 40 to 15,000 cycles is obviously a balanced system. We know that in such a system a change in the high frequency cut-off to 11,000 cycles or a step of -1 LIM, is just discernible. Under practical listening conditions, this is an exceedingly subtle difference, and it is reasonable to assume, and experience confirms, that the change in aural balance is also exceedingly slight and is undoubtedly still satisfactory. In the light of experience, it appears likely that the balance is also satisfactory for a further reduction to 8,000 cycles (-2 LIM). On this basis, then, a low-frequency cut-off of 40 cycles is adequately balanced by a high-frequency cut-off of 8,000 cycles or higher. Likewise, if one liminal unit at the low frequency end corresponds to 80 cycles, as suggested by Gannett and Kerney, then a high-frequency cut-off of 11,000 cycles or higher would be adequately balanced by a low-frequency cut-off of 80 cycles or lower. These conditions have been plotted in Fig. 12, along with the constant product data, which leads to an area of satisfactory aural balance indicated by cross-hatching. This indicates that there is considerable latitude in the choice of cut-off frequencies above about 8,000 and below about 80 cycles. This is as we would expect it in view of the rather low probable intensity levels in the end regions.

Another criterion of balance is that which results from the pairing of low and high cut-off frequencies which in judgment tests have yielded equal reduction in quality in the opinion of listeners skilled in such observations. Such a curve, Fig. 12, has been obtained from the data of Snow[9]. Above a high-frequency cut-off of about 6,500 cycles, this curve gives higher values for the low cut-off than a constant product of 640,000 and is well within the postulated area of balance. It will be observed that Snow's data would also suggest higher values of low-frequency cut-off for frequency bands less wide than 6,500 cycles.

With all of the above considerations in mind, and remembering that popular preference is on the side of what may be termed "full" rather than "light" treatment of the bass, it seems reasonable to propose the relationship indicated in Fig. 12 as an objective for good engineering practice. The possible advantages of the proposed relationship are that it (1) provides a definite basis for calculations, (2) establishes an approximate mean of the extreme criteria which might be applied, and (3) is in the direction of relatively economical low-frequency components. It should be pointed out again that balance requirements are not rigid and considerable latitude is possible in acceptable reproducing systems. Moreover in practical systems, the response usually trails off gradually at the ends of the range rather than presenting a sharp cut-off, and it is necessary to consider the contributions from the "skirts" of the charactertistic in appraising the aural balance situation. In a system in which the low cut-off is undesirably high in the frequency range an impression of balance may be created by accentuating the response in the region just above the cut-off.

A Preferred Series of Frequency Bands

From all of the foregoing, it is possible to construct a rational series of audio frequency reproduction bands with equal, just discernible differences in band width. This may be done by successive reduction of the high-frequency cut-off in steps of 1 LIM and assigning the corresponding low-frequency cut-off from the aural balance relationship just previously developed.* Uniform transmission between cut-off frequencies is assumed. Such a series is extremely useful in appraising the whole problem of higher fidelity, in classifying reproducing systems and program sources on a basis of relative merit from a standpoint of frequency range, and in setting realistic engineering design objectives.

Table 1 presents 8 such bands ranging from the complete music spectrum (40 to 15,000 cycles) to what is probably the lower limit of usefulness for the reproduction of music (200 to 3,000 cycles)[7]. It is probable that a band must be changed by two numbers rather than one if really marked differences under ordinary listening conditions are sought. Explanatory notes are appended to the table, relating the bands to existing program sources and listening conditions.

*This is not the same as a series of bands providing equal judged quality differences. The 1 LIM differential basis was used instead because published quality judgment data is very limited in scope and more test work is needed. However, Snow's results (loc. cit.) indicate that for the principal bands of interest (Nos. 3 through 6) the differences are approximately equal percentages of judged quality.

Table 1. A Preferred Series of Audio Frequency Bands for Sound Reproducing Systems.

Band Number	Classification	Cut-off Frequencies Low	High
1	High Fidelity	40	15,000
2	High Fidelity	65	11,000
3	High Fidelity	75	8,000
4	Medium Fidelity	90	6,400
5	Medium Fidelity	110	5,300
6	Medium Fidelity	130	4,400
7	Low Fidelity	160	3,600
8	Low Fidelity	200	3,000

A. *Band* 1 *is the assumed complete spectrum of music. FCC requirements for FM transmission call for a range of* 30 *to* 15,000, *uniform within* 2 *db.*

B. *Band* 2 *affords as complete fidelity as Band* 1 *for a critical listener* (5% *most acute hearing*) *in very quiet homes* (5% *quietest,* 33 *db noise level*) *at usual reproduction levels.*

C. *Band* 3 *affords as complete fidelity as Band* 1 *for an average listener* (*median population hearing*) *in an average home* (*median annual noise level,* 43 *db*) *at usual reproduction levels.*

D. *Band* 2 *or* 3 *is approximate maximum range of high quality transcriptions.*

E. *Band* 5 *or* 6 *is approximate maximum useful range for nighttime and rural reproduction of AM broadcasting and commercial lateral phonograph records.*

F. *Bands* 2 *to* 6 *probably require console type radio receivers for reproduction of low end.*

G. *Aural balance will probably be acceptable if one cut-off is paired with that in an adjacent band. Thus*: 65-90 to 8,000; 90-130 to 5,300, *etc.*

It is evident that the whole fidelity problem is a relative one, in which listening conditions, the band width available from program sources, and the important matter of cost in its relation to real value to the listener, must be carefully considered. In FM and improved phonograph transcriptions, there are the potentialities for a substantial improvement in the quality of service. It has been shown that on a statistical basis, the range from 75 to 8,000 cycles will provide the same perceivable frequency range for the average listener at the usual reproduction levels as would reproduction of the whole music spectrum from 40 to 15,000 cycles. With the exception of a slight difference in the low frequency limit this conclusion is in accordance

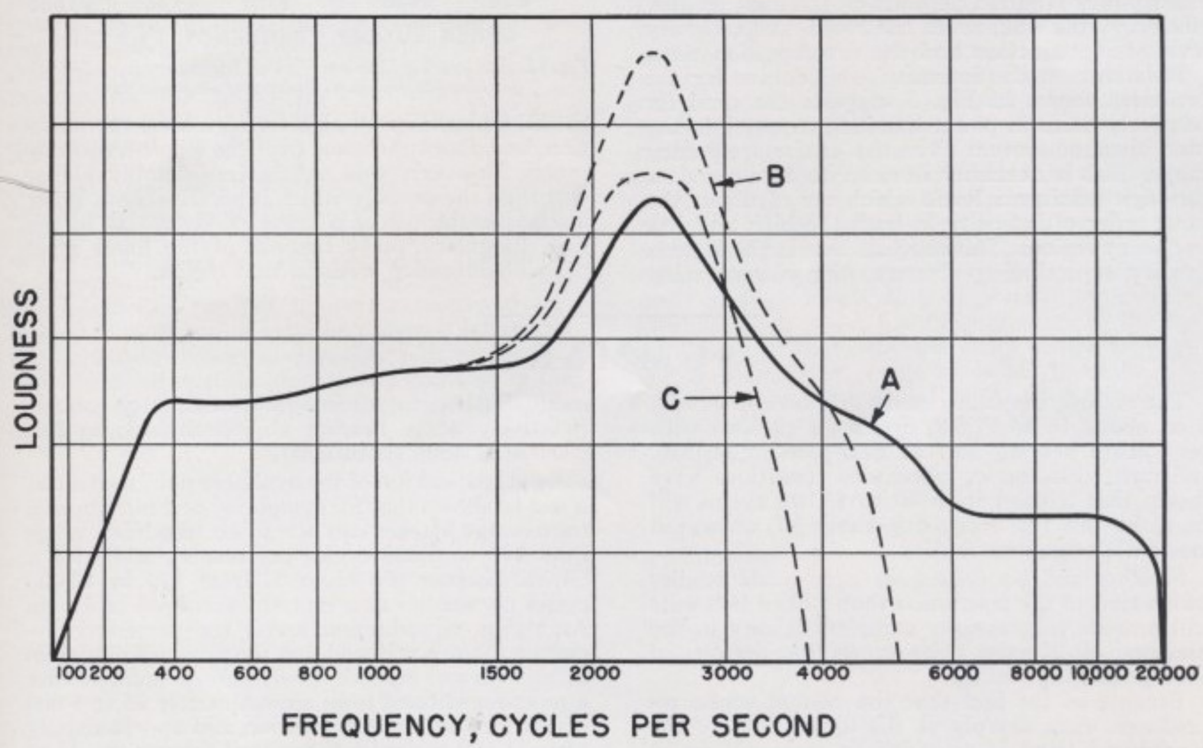

Fig. 11. *Loudness Versus Frequency for a Symphony Orchestra. Curve A is for Live Listening. Curve B Approximates the Conditions for Reproduction Over a Loud Speaker with Excessive Middle High Frequency Response. Curve C Approximates the Result of Use of Tone Control by the Listener to Reduce Excessive Stimulation in the* 2,000 *to* 3,000 *Cycle Region.*

with Fletcher's suggested range of 60 to 8,000 cycles, made after a study which included not only the orchestra but also most of the individual instruments.

The term "High Fidelity" deserves careful use. If the term is to retain any meaning, it does not seem to be proper to apply it to a band less narrow than No. 3 (75 to 8,000 cycles). The term "Medium Fidelity" seems appropriate for Bands 4 and 5 (down to 110 to 5,300 cycles), while narrower bands, in view of the present state of the art are "Low Fidelity" in their performance.

Power Requirements

The reproduction of symphony orchestra music in a fairly large living room at concert hall levels would require an average acoustic power of about 5 milliwatts. The peak power in brief intervals may be 20 db higher than the average, so the peak acoustical power required is 0.5 watts. If the loud speaker is 10% efficient, it would therefore require a peak electrical input of 5 watts. It is usually found to be desirable to provide amplifier capacity considerably in excess of this figure to keep the distortion to low values.

The more usual maximum levels in the home are about 20 db below concert hall levels. This requires a peak electrical power of 50 milliwatts and an average electrical power of about 0.5 milliwatts. The exact power required depends on the loud speaker efficiency, the volume of the room, the intensity level of reproduction and the reverberation time.

Reference to the intensity level curves for the orchestra shown in Fig. 6 suggests the need for relatively uniform power handling capacity in the loud speaker system over the entire frequency range. This is necessary in order to accommodate the high maximum levels which are of about the same order of intensity in both the high and low frequency regions. This suggests that in the highest quality reproducing systems, the power rating should be sufficiently high for high level reproduction, and about the same over the whole frequency range. However, this entails considerably higher cost than the practice which is permissible at lower levels, i.e. the use of a lower power rating in the high frequency range because of the lower most probable intensity levels in that region.

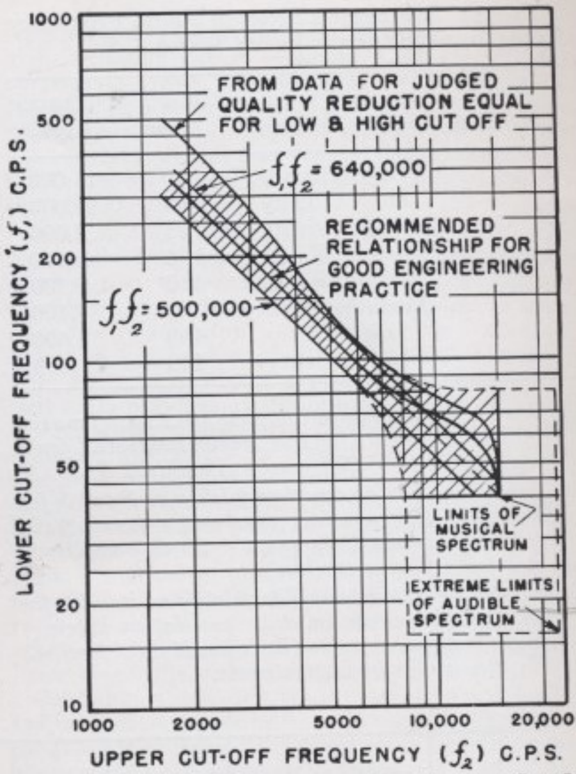

Fig. 12. Relationship Between High and Low Frequency Cut-offs for Satisfactory Aural Balance of Reproduction.

SUMMARY

The audible frequency range is known to extend from about 16 to 22,000 cycles for persons with very acute hearing and at near-pain intensities. Judgment tests under laboratory conditions have shown that a band from 40 to 15,000 cycles will transmit the full frequency range of orchestral music with complete fidelity.

Fletcher and his colleagues have made studies which lead to the conclusion that a band less wide will provide substantially complete fidelity in the presence of average noise levels for persons of average hearing ability.

Because of the fact that the cost of sound reproducers rises sharply as the upper limit of the reproduced band is extended, it is important to establish the perceivable frequency ranges at the usual home reproduction levels for an average listener (average hearing ability situated in average residential noise conditions) and for a critical listener (relatively acute hearing ability situated in low residential noise conditions).

By statistical use of the available published data, it can be shown that for symphony orchestra music, the average listener can perceive a frequency range from 175 to 5,800 cycles per second, while for a critical listener the range is from 120 to 12,000 cycles per second at a reproduction level of 55 db. At higher reproduction levels the perceived frequency range is widened, but the principle of liminal differences and balance considerations indicate that a reproduced band from approximately 75 to 8,000 cycles for the average listener, and approximately 65 to 11,000 cycles for the critical listener, would be practically indistinguishable from unlimited band reproduction over the usual range of reproduction levels in the home.

These data are believed to be useful in the economical attainment of practical high-quality and medium-high-quality sound reproducing systems generally, as well as setting upper limits for quantity produced home radio receivers. The average listener criterion closely approximates the situation in moving picture theatres, while application of the critical listener criterion enables us to predict the requirements for concert hall and broadcast monitoring applications. It is estimated that for large quantity applications, the cost of components for a satisfactory 11 kc reproducing system would be roughly half that for a 15 kc system, while an 8 kc system would cost approximately one-fifth as much as a 15 kc system. These cost indications refer to systems of the same power rating, and suitable generally for use in the home as a part of a broadcast receiver.

It is pointed out that the loudness contribution for music is greatest in the 2,000 to 3,000 cycle region despite the fact that the highest maximum and most probable intensity levels are lower down in the frequency scale. When the loud speaker is chosen largely on the basis of loudness efficiency (accentuated response in the 2,000 to 3,000 cycle region) many listeners prefer to accept the excessively restricted high frequency range resulting from advanced setting of the conventional tone control, to obtain relief from an otherwise annoyingly "shrill" effect. The need for such an undesirable compromise is avoided when loud speakers designed for level middle high frequency response and proper spatial distribution of the high frequency sound, are used.

Experience has taught that the low frequency cut-off must be properly related to the high frequency cut-off for the most pleasing aural balance of reproduction. A new relationship for the cut-off frequencies is proposed which averages the previous constant product limits for restricted frequency ranges, and at extreme ranges is influenced by liminal differences and quality judgment data. The end result is in the direction of economy in the reproducing system while adequately fulfilling fidelity requirements.

A preferred series of eight audio frequency bands is constructed with the high frequency cut-offs differing in steps of 1 LIM and with corresponding low-frequency limits determined from the above aural balance relationship. The step from one band to another is probably barely discernible as a difference in band width for music. For the more important bands, the differences yield closely equal steps of "quality." These preferred bands are thought to be useful for classifying sources and reproducing systems, in ascertaining the probable change in quality of a system due to changes in band width, and in establishing realistic engineering specifications.

It is shown that very substantial improvements in quality can be realized without attempting to reproduce the entire music range of 40 to 15,000 cycles per second. It has been shown on a statistical basis that a band from 75 to 8,000 cycles will provide the same perceivable frequency range for the average listener, as will reproduction of the whole range from 40 to 15,000 cycles.

It is suggested that the term "High Fidelity" be limited to bands of 75 to 8,000 cycles and wider. Suggestions as to the classification of the other bands as "Medium Fidelity" and "Low Fidelity" are given.

The power required for the reproduction of music is briefly discussed. If it is desired to reproduce at concert hall levels in the home, a peak electrical power of about five watts must be delivered in brief intervals to the loud speaker. The required power is a function of the sound intensity, the volume of the room and its reverberation time. The usual maximum listening levels in the home would be about 20 db below concert hall levels and this would correspond to a peak electrical power of about 50 milliwatts. The average electrical power at this level would be about 0.5 milliwatts.

For the reproduction of symphony orchestra music at high levels, it is important to provide adequate peak power handling capacity in the reproducer over the entire frequency range. In high quality systems, it seems advisable to make the power rating of the sound reproducer about the same over the entire frequency range.

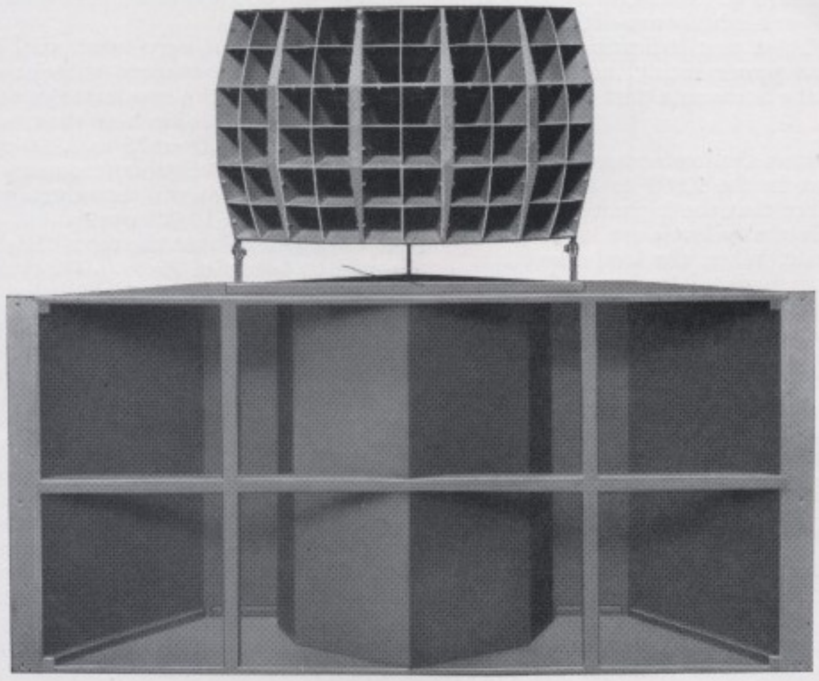

Plate B. Extended Range Reproducer System as Manufactured by Jensen Manufacturing Company for use with Sound-on-Film and Heavy Duty Sound Reinforcement Applications.

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While radio and electronic progress has been accompanied and enriched over the years with pertinent and ample technical literature, the field of electro-acoustics has suffered for lack of such informational material. Books and articles have been either too abstruse for any but the highly trained engineer or too meagre to cover the field. But this is an age when the use of reinforced and reproduced sound is closely joined to the everyday life of nearly every one of us and sound is, therefore, an important subject of both academic and professional interest.

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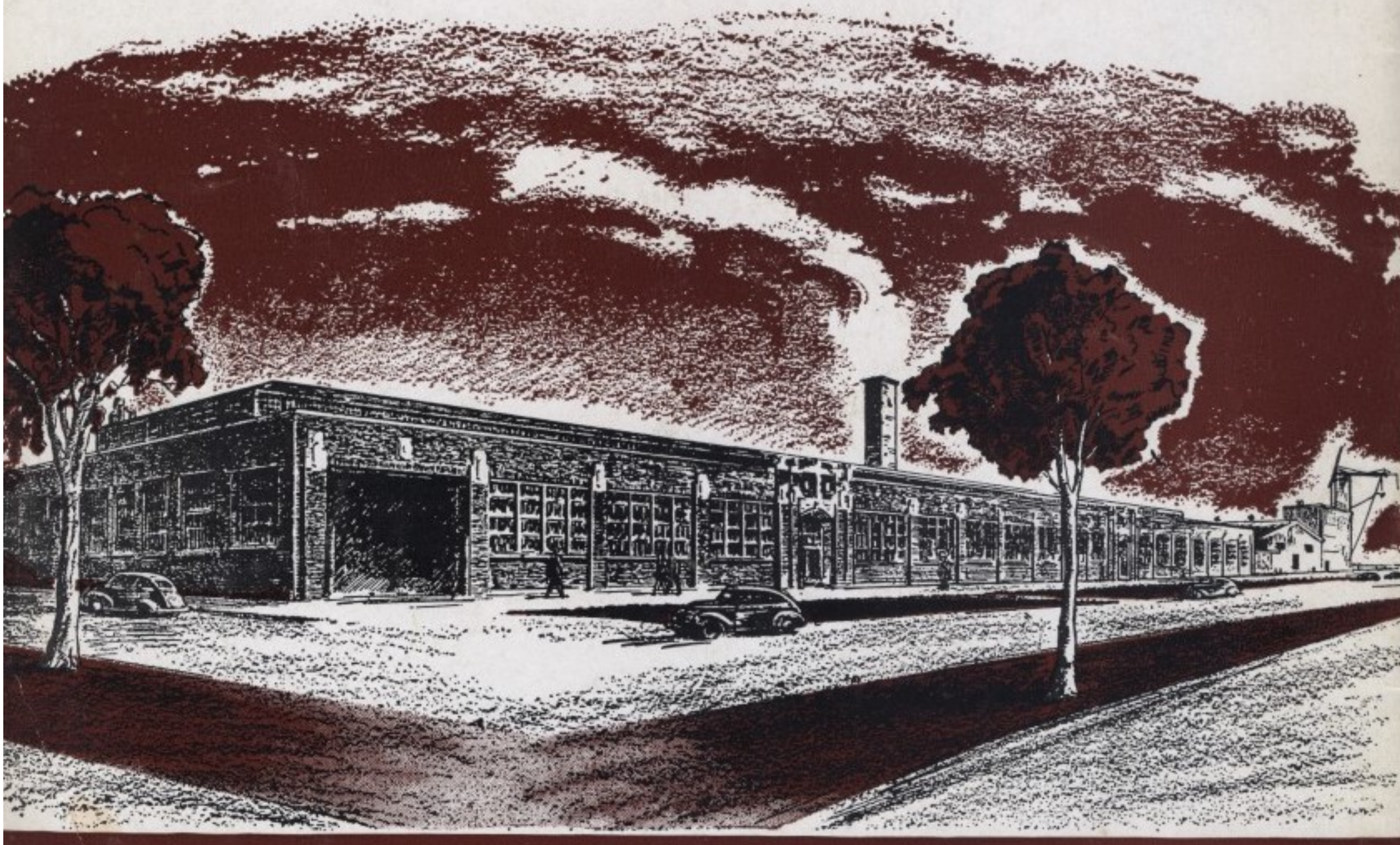

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