More About Audio-Frequency Amplifiers

By SYLVAN HARRIS

This, the third of Mr. Harris' series on A.F. amplifiers, deals with their performance from the hearers' standpoint. The first article was devoted to general requirements, and the second to graphic methods of representing characteristics.

THE study of audio amplifiers, which we are making month by month in RADIO NEWS, is becoming very fascinating; for it has led, and is leading, to many important considerations which are quite new to us. Although it might be supposed, without careful reflection, that the study of amplifiers is a purely *electrical* subject, enough has already been brought out in these articles to show that the fact is otherwise. The two previous discussions in this series contained very little about transformers or other coupling devices, considered as electrical apparatus; but dealt with matters of the utmost importance as regards their *output*, which must be judged from an acoustical standpoint.

The first article described, in some detail, the nature of overtones as well as fundamental tones, explaining their importance and the necessity of preserving them, and showing the effects of imperfect amplification on the reproduced voice and speech. The second of the series showed how the characteristics of an amplifier are best plotted in graph form, in order to express the physiological phenomena of reproduced sound in the manner most readily comprehended by the sight.

This article continues the discussion begun in those proceding it, and deals with the requirements which successful transformers must satisfy. As the principles which we have already set forth apply with equal force to all types of amplifier coupling devices, we will not confine this series to transformers, as first planned; but extend its scope to include other types of coupling, resistances, impedances, etc.

As said at the conclusion of the previous article, we must deal only with *practical* requirements for amplifiers. It is obvious that no apparatus is perfect or can be made to function perfectly. For practical purposes, however, it may often be made to operate so well that the human senses cannot perceive any lack of perfection.

WHAT TOLERANCE IS PERMISSIBLE?

To make this observation appropriate to our discussion, and explain our meaning, let us consider the characteristic curve of a specific, actual amplifier, and compare it with that of the imaginary, perfect amplifier. The question to be answered is, how far may the actual characteristic depart from the line of perfection before any distortion in the reproduced speech or music can be detected by the human ear?

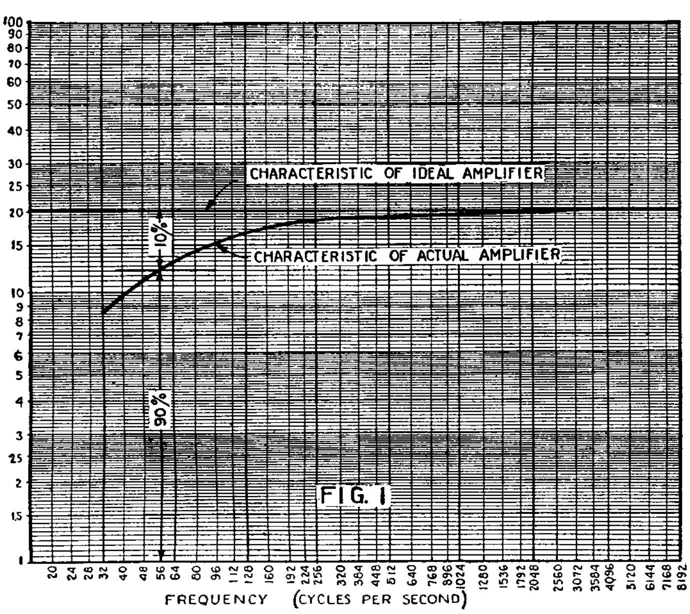
As Fig. 1 shows, the perfect amplifier would deliver a voltage amplified at a uniform ratio at all frequencies; no matter what the pitch of the tone amplified, its strength would always be equally increased. In other words, the voltage output of the amplifier would *always* be the same number, say twenty, times the input voltage.

But, as we see from the characteristic curve of the actual amplifier, and as explained in detail in the previous articles, in practice the amount of voltage amplification drops rapidly at the lower frequencies. To find out the amount of this drop which is permissible, we must set up standards based on the phenomena of *audition* or hearing, as they have been determined by experiment.

In other words, we must answer two questions: first, "What is the lowest frequency we may ever want to pass through the amplifier?" and second, "At this frequency, to what extent may the voltage ratio drop before the effect is noticeable by the human ear?"

The correct answer to these questions will enable us to set the standards by which transformers may be judged. At the present time it is unnecessary to know more than this about amplifiers. In the past more would have been required, for a few years ago there were serious defects in amplifiers, causing decided humps in the characteristic curves anywhere along their length —even in the middle. But in the past year or so manufacturers have learned how to smooth out these humps, and have produced transformers with virtually flat curves up to six or seven thousand cycles, which is fairly near the upper-frequency limit of audibility.

The most important part of the curve, therefore, is the low-frequency end, to which we will confine our attention for the present.

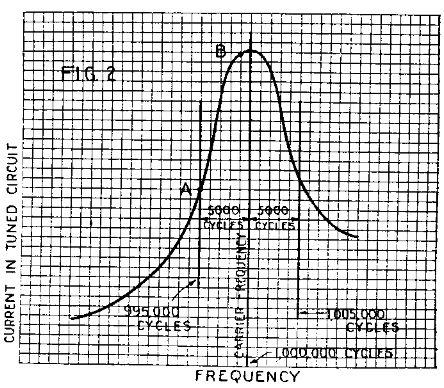


The ideal amplifier would amplify equally well at any frequency, as indicated by the straight horizontal "curve" in this chart; but the voltage ratio of the actual amplifier drops with increasing frequency, as indicated by the lower curve. There is a limited drop of voltage ratio which is permissible, depending upon the ability of the human ear to detect changes of sound volume. Change of sound-volume in the loud speaker depends considerably upon the change of voltage-ratio; so that the amplifier should be considered, as we do here, from the audition view-point.

It is well known that the lower-frequency limit of audibility is in the neighborhood of 32 cycles per second, and for some ears even higher than this. Certainly there are very few persons who can perceive tones having frequencies lower than this, which is that of the lowest note on the piano. The bass viol goes only as low as 40 per second.

DO WE NEED THE LOWEST TONES?

If those readers who are pianists will reflect for a moment on the number of times they strike a note in the last octave, they will agree with me that these are extremely few. Furthermore, it is doubtful whether the bass viol player uses his lowest note, the open E, except on rare occasions; and even the two notes above this are seldom played.

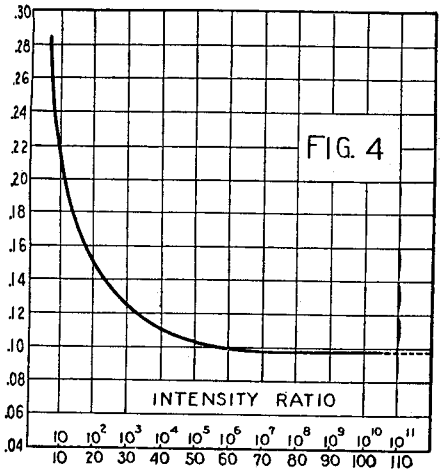


One cause of distortion in radio receivers; when the tuning of the R.F. stages is too sharp, or too much regeneration is used, the bands on either side of the carrier frequency, which correspond to the voice or musical frequencies, are cut off, so that the quality of reception is impaired.

In view of this, let us assume arbitrarily that the lowest frequency we expect our amplifier to reproduce is 50 cycles per second, which is low enough for all practical purposes. This eliminates only the three lowest tones of the bass viol and the six lowest of the piano. With regard to the organ, there are certain of its longest pipes which will not be heard; but we must be reasonable, for prohibitive costs may not be incurred solely to take care of the notes down to 32 cycles.

Incidentally, it must not be thought that any of the amplifiers now in general use will reproduce the very low frequencies under all conditions. It will be seen, later on, that even the resistance-coupled amplifier will slight the low tones, unless it is carefully designed. Furthermore, it must be kept in mind that the loud speaker may be a source of serious distortion; as well as the radio-frequency amplifier with its regeneration. Defects in these should not be blamed on the audio amplifier; but, although this series of articles is devoted to the latter only, we shall show that in some cases it may be possible to *compensate* in some degree for the defects of the former.

Having decided that 50 cycles per second is the lower-frequency limit for our discussion, let us find out how much the voltage ratio may be permitted to drop at this frequency before our ears discover the effect; or, in other words, how small a change in sound intensity is noticeable. In some cases the effects are detected at once in the out-



The vertical scale represents fractional change of energy in the sound wave. This curve shows the faculty of the human ear to perceive a change of sound intensity.

put of the loud speaker; we have heard people say that a certain loud speaker "has a high pitch," or "a low pitch." This is an inaccurate way of putting it, as the loud speaker does not, or should not, have a pitch of its own. What is meant by the expression is that the speaker reproduces the high tones well but neglects the low tones, or vice versa.

MATCHING THE AMPLIFIER WITH A LOUD SPEAKER

A part of this effect is often caused by the amplifier, and it may well happen that a "high-pitched" amplifier connected to a "low-pitched" loud speaker may produce very satisfactory results. For intance, if our amplifier is weak on the low tones and strong on the high ones, we might advantageously use a loud speaker which has an opposite or "complementary" characteristic, so that it will reproduce the low tones strongly and the high tones somewhat more weakly. On the other hand, if the amplifier is as strong on the low frequencies (down to 50 cycles) as it is on the higher ones—in other words, if it has a "flat" characteristic—then we should use a loud speaker which has also a flat characteristic. The proper selection of the combination introduces the "compensation" of which we have previously spoken.

There is another important consideration—that of the "side-bands" of the carrier wave transmitted by the broadcast station. It is possible that the tuning of the transmitter and of the R.F. amplifier of the receiver may be so sharp as virtually to cut off some of these side bands. This is especially possible with a regenerative receiver. The effect is illustrated in Fig. 2, which shows how the current in the tuned R.F. circuit varies with the setting of the condenser, when tuning to the carrier wave of a particular frequency. The side bands, which are produced by modulating the carrier wave with vocal or musical frequencies, extend about 5,000 cycles higher and lower than the carrier frequency. A carrier wave of 300 meters (1,000 kilocycles), for instance, modulated by musical frequencies up to 5,000 cycles, would include all frequencies between 995,000 and 1,005,000 cycles; although in a small band of 50 cycles on each side of the carrier frequency the tones would be inaudible.

It is obvious from Fig. 2 that the current in the tuned circuit of the receiver, when a tone of 5,000 cycles modulates the carrier wave (as shown at A), is less than that when a tone of 1,000 cycles is being received. As a consequence, we may expect that the high-frequency tones will be impressed on the audio amplifier at a lower voltage than the low-frequency tones. If this is the case, it may be advisable to use an amplifier with a *rising* characteristic, such as that shown in Fig. 3, to bring back the high notes to their full strength. All this, of course, is only in case we use a loud speaker which has a *flat* characteristic. If the loud speaker, on the contrary, is strong on the high notes, we can use an amplifier with a flat characteristic, for the loud speaker will do the compensating. If the loud-speaker is weak on the high notes and a flat-characteristic amplifier is used, the effect will be accentuated, and we may find the violin sounding like a 'cello, as explained in the first article of this series.

However, we will assume for the present that we have a loud speaker with a flat characteristic; if such a one is not available at the present time, it will be very shortly. We will assume also that the R.F. stages do not cut the side bands appreciably, for, if properly designed and operated, they will not do so. In this case what we require is an amplifier with a characteristic curve as nearly flat as possible.

SENSITIVITY OF THE HUMAN EAR

How flat should this be? This question may be answered by consideration of the results of the research into audition which has been made by Mr. V. O. Knudsen (Phys. Rev. xxi, No. 1, Jan., 1923). Some of this work is summarized graphically in a chart (Fig. 4), here reproduced by permission from the Bell System Technical Journal, in which it illustrated a paper by Dr. Harvey Fletcher (Oct., 1923). Without going too deeply into the analysis of this chart, it represents on the vertical scale the fractional change (called the "Fechner ratio"), in sound energy which is just perceptible to the ear. Thus, if E represents the intensity of a tone, and this is increased to an amount represented by ΔE, the ratio of the increase to the initial intensity, E, is the Fechner ratio. The horizontal scale represents simply the values of the intensity E. In other words, Fig. 4 shows how the least perceptible *percentage of change* in the loudness of tone varies with the loudness.

For tones above a certain intensity, as the chart shows, the fractional change in their loudness that is just perceptible is very constant, and has a value of 0.1; in other words, between very wide limits of intensity, we can perceive a change of ten per cent. in the loudness of a sound. Also, this means that we can tolerate a drop of voltage, at the *output* of our audio amplifier, of about 10 per cent. Note that the word *output* is emphasized. The amount of voltage drop tolerable in *each* stage of the amplifier depends upon the number of stages. If we use two stages, as in transformer-coupled amplifiers, the voltage amplification available at 50 cycles must be 94.9 per cent. (or the square root of .90 — for $.949 \times .949 = .90$) of that which is available at the higher frequencies. If there are three stages of A.F. amplification, as in resistance- or impedance-coupled amplifiers, each stage must supply at 50 cycles 96.6 per cent. of the voltage amplification available at the high frequencies (for $.966 \times .966 \times .966 = .90$).

To sum up, then, in two-stage A.F. amplifiers, the falling off of the curve, at 50 cycles, from the value at the higher frequencies should not be more than 5 per cent.; and in three-stage amplifiers, not more than 3.5 per cent. How near to these values the amplifiers now on the market approximate it is difficult to say; but at least they come considerably nearer to them than did the amplifiers available a year or so ago.

SOURCES OF DISTORTION

This article has become sufficiently long at this point, so that we can go no further this month into the subject; but we have at least established a criterion by which to judge the efficiency of amplifiers and to guide in their design. We will consider its application to particular cases in the subsequent numbers of this series.

Thus far we have considered amplifier coupling devices solely with regard to the frequencies transmitted by them. There is yet another important item which has been very much neglected by other writers and investigators; but which is of such importance that an amplifier which has a perfectly flat frequency characteristic may yet introduce serious distortion into the reproduction.

What I am referring to is the response of the amplifier under signals of various strengths. That of the electron tube is limited by the charge, which collects upon the grid and under certain conditions becomes sufficiently great as to introduce considerable distortion. But if the input circuit of the tube is designed to have relatively low resistance, no fear need be felt on this score, excepting in so far as the overall amplification is reduced.

Assuming that no such overloading of the grid occurs, there is yet another cause of distortion, which occurs especially in transformers, where the voltage ratio changes with the signal strength. Under some conditions, and since these coupling devices are generally designed to transmit very little power, their voltage regulation is very poor; and when the signal strength exceeds a certain limit the voltage ratio may fall considerably. This is another phase of the amplifier problem, which will be considered in detail in the next article of this series.

In this forthcoming article, also, we shall give in graphic form the results of some of the measurements which have been made on various types of coupling devices, in the Radio News Laboratories during the past few months.

An A.F. amplifier with a rising frequency-characteristic can be used to advantage in many cases, especially where the R.F. amplifier is tuned so sharply as to cut off some of the side frequencies, or at least to reduce them in intensity. The increased voltage step-up in the coupling device, as the frequency becomes higher, will compensate for the weakening of the high notes on account of the very sharp tuning. Also a loud speaker which is full on the low tones, but weak on the high ones, will act better with an amplifier having a characteristic like this.