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TELEVISION TECHNICAL ASSIGNMENT

AUDIO FREQUENCY AMPLIFACTION

739D

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INTRODUCTION

In radio, and in sound work in general, where it is desired to amplify at audio frequencies, there are three principal sources of sound to be considered: the microphone, the phonograph pickup, and the detector output of a radio receiver. To these may be added the sound-on-film picture and television photoelectric pickup device.

Amplifiers for all the purposes mentioned above will have somewhat similar characteristics with the exception of the television amplifier. Video (television picture) amplifiers differ widely from the ordinary audio amplifier because of the very wide band of frequencies to be amplified.

The principal reasons for difference in the design of audio amplifiers will lie in the amount of gain, the power output and the degree of fidelity required. The audio amplifier to be used in the home radio receiver need deliver only sufficient power output to operate a single dynamic reproducer. With modern high-gain i.f. amplifiers it is possible to assume for ordinary purposes a comparatively high voltage output from the detector. Thus, the audio amplifier for the ordinary home receiver requires neither very high gain nor very great power output. The degree of fidelity depends on the type of receiver. Obviously, a high-fidelity amplifier in a midget receiver would be misdirected effort since the reproducer in such a receiver is incapable of high-fidelity reproduction. In the larger receivers fidelity may be a prime factor in design.

On the other hand, it may be necessary to design an amplifier for a public address system to be used in a large stadium, aviation field, or for some similar service, where a very large output is required to operate several reproducers. It may be necessary to operate this amplifier from a microphone, phonograph pickup, or radio receiver, interchangeably. As previously explained, the radio receiver and phonograph pickup may be expected to give a comparatively high output but the output from microphones will ordinarily be quite small. Hence, such an amplifier must be designed for both high gain and large output. The overall fidelity will be a function of the type of service. An amplifier designed for inter-communication needs or speech broadcast will not require the overall fidelity of one designed for musical entertainment. Somewhat similar conditions exist in an audio power distribution system where the output of the individual reproducer is small but where a large number of such reproducers must be operated from a single amplifier. This condition would be exemplified by a large hotel installation where a common amplifier feeds a reproducer in each room.

DECIBEL CALCULATIONS

Before taking up the actual design of audio amplifiers, some idea of the methods of measuring and calculating audio voltage gain and power output is required. In audio frequency work, it is customary to speak of input power level, power output, and gain in terms of decibels (abbreviated db) instead of watts. Numerous tests have indicated that the response of the human ear is *approximately* proportional to the logarithm of the stimulus. Hence, a logarithmic measure of power will more closely approximate the amplifier performance as interpreted by the human ear. The ear can just distinguish the difference between two sound levels that differ by one db.

A decibel may be defined as ten times the common logarithm of the ratio of two powers, or mathematically

$$\text{Gain in db} = 10 \log_{10} \frac{P_2}{P_1}$$

where P_2 is the power output, or power at the receiving end, and P_1 the power input or power at the transmitting end. The decibel may be used in either of two ways, first, as the measure of the difference between any two sound levels, and second, as a measure of the difference between any given power level and an arbitrarily selected reference level. In audio frequency work this reference level is taken as .006 watt, meaning P_1 = .006 w.

As an example of the first case find the difference between a power level of 20 watts and one of 30 watts.

$$\begin{aligned} \text{db} &= 10 \log_{10} P_2/P_1 \\ &= 10 \log_{10} 30/20 \\ &= 10 \log_{10} 1.5^* \\ &= 10 \times .176 \\ &= 1.76 \text{ db} \end{aligned}$$

* (Log_{10} 1.5 = .176 from tables)

Thus, 30 watts is only 1.76 db greater than 20 watts. To the human ear this would represent a hardly distinguishable increase in volume.

To illustrate the second case, assume the maximum undistorted power output of an amplifier is 12 watts. What is the output level in db?

$$\begin{aligned} \text{db} &= 10 \log P_2/P_1 \\ &= 10 \log 12/.006 \\ &= 10 \log 2{,}000 \quad (\text{Log}_{10}\ 2{,}000 = 3.3 \text{ from tables}) \\ &= 10 \times 3.3 \\ &= 33 \text{ db} \end{aligned}$$

Thus, 12 watts is 33 db above the reference level of .006 w. In this case a power level of .006 w is taken as zero db. In terms of the first illustration the difference between a power level of .006 watt and 12 watts is 33 db.

Referring to the receiving tube manual, it is seen that an output of 33 db could be obtained from two Type 46 tubes operated in push-pull Class B, two Type 6F6 tubes operated in push-pull Class AB, or two Type 6L6 tubes operated in push-pull Class A.

Assume the output voltage of a detector developed across a 120,000-ohm load resistance is 12 volts r.m.s. The power output E^2/R is $12^2/120{,}000$ or .0012 watt. Expressed as a power level in db in reference to zero level this will be

$$\begin{aligned} \text{db} &= 10 \log .0012/.006 \\ &= 10 \log .2 \\ &= 10 \times (-1 + .3) \end{aligned}$$

Since the mantissa of a logarithm is always positive, the multiplication is performed as follows:

$$\begin{array}{r} \bar{1} + .3 \\ \underline{10} \\ -10 + 3.0 = -7 \text{ db} \end{array}$$

Therefore, .0012 watt represents a power level of -7 db in reference to the arbitrarily selected reference level .006 watt. In amplifier parlance the detector output is said to be down 7 db from the reference level.

The gain necessary in an amplifier, assuming all impedances are properly matched, will be the difference between the input and output power levels. Thus, to raise the detector output of .0012 watt to a level of 12 watts will require a total gain of 7 + 33 or 40 db. This can easily be checked by solving for the difference in power levels between .0012 w and 12 w.

$$\begin{aligned} \text{db} &= 10 \log 12/.0012 \\ &= 10 \log 10{,}000 \\ &= 10 \times 4 \\ &= 40 \text{ db} \end{aligned}$$

The total gain required in an amplifier depends on two principal factors, the input power level available and the output level desired. In any practical installation, the amount of gain must be variable over comparatively wide limits since there will be times when the maximum output will not be desired and other occasions, such as when a speaker fails to speak directly into a microphone, when the input level falls well below that taken as average for the microphone. In the design of an amplifier the gain should be variable over a range of ten to twenty db to allow for this variation in input level.

In amplifying the output from the detector of a modern radio receiver, it is usually possible to obtain almost any desired signal level, and for design purposes this output can be assumed as zero db. Thus, the gain necessary in the receiver audio amplifier for an output of 12 watts will be approximately 33 db.

The power output of phonograph pickups varies over wide limits. A good magnetic type pickup may have an output approaching zero db while one of the crystal type may have an output in the order of -30 db. In the absence of definite information -15 db may be assumed as average. Any variation in level when changing from one type of pickup to another can usually be compensated for by an adjustment of the gain control.

The power output levels obtained from microphones also varies over wide limits. The output of a good double button carbon microphone may vary from -60 to -30 db. The output from dynamic and velocity microphones will be somewhat lower than that of the average carbon microphone. For main amplifier design purposes an average microphone output of -45 db may be assumed. A pre-amplifier is usually used between the microphone and the main amplifier particularly when the main amplifier is expected to work interchangeably from a microphone and (or) a pickup or radio receiver. In the example previously cited, if the main amplifier has a gain of 33 db, to maintain an output of 12 watts the pre-amplifier should have an approximate gain of 45 db to bring the output of the microphone up to zero level. The pre-amplifier should also be designed to provide a quite wide variation in gain. A variation from 15 to 20 db is usually satisfactory for control purposes.

Just how much power do these minus db levels represent? It is often necessary to know the actual amount of power at minus db level and, conversely, when the actual power is known, it may be necessary to express the level in decibels. The procedure for making such calculations is exactly the same as in the case of positive power levels, that is, powers above .006 w, but more care is required. If there is any difficulty in understanding the following examples, the student should thoroughly review the assignment on logarithms.

EXAMPLE 1: Given an input signal level of -30 db. Convert to milliwatts.

$$\text{db} = 10 \log_{10} \frac{P_2}{.006}$$

$$-30 = 10 \log_{10} \frac{P_2}{.006}$$

Dividing by 10

$$-3 = \log_{10} \frac{P_2}{.006}$$

Antilog -3 = .001

$$.001 = \frac{P_2}{.006}$$

$$P_2 = .001 \times .006 = .000006 \text{ w}$$

$$= .006 \text{ mw}$$

or,

$$-\text{db} = 10 \log_{10} \frac{.006}{P_2}$$

$$-(-30) = 30 = 10 \log_{10} \frac{.006}{P_2}$$

$$3 = \log_{10} \frac{.006}{P_2}$$

$$1000 = \frac{.006}{P_2}$$

$$P_2 = \frac{.006}{1000} = 6 \times 10^{-6} \text{ watts}$$

EXAMPLE 2: Given an input signal of -15 db. Convert to milliwatts. Observe the procedure very carefully. Remember *the mantissa is always positive and to divide a negative characteristic it must first be made evenly divisible by the divisor.* The decibel is simply a logarithm multiplied by ten and so *must be treated in every respect mathematically as if it were itself a logarithm.*

$$\text{db} = 10 \log_{10} \frac{P_2}{.006}$$

$$-15 = 10 \log_{10} \frac{P_2}{.006}$$

$$\frac{-15}{10} = \log_{10} \frac{P_2}{.006}$$

If the power level were +15 db, the division by ten would result in a quotient of 1.5; however, it is -15 db and this must be treated *as the negative characteristic of a logarithm.*

$$\begin{array}{r} -15 + 0.0000 \\ -\ 5 + 5.0000 \\ \hline 10\ \overline{)-20 + 5.0000} \\ -\ 2 + \ .5000 \end{array}$$

Adding -5 + 5 to the characteristic -15 does not change the absolute value of -15 but this procedure does make the negative characteristic exactly divisible by 10. Therefore

$$\frac{-15}{10} = \log_{10} \frac{P_2}{.006}$$

$$-2 + .5 = \log_{10} \frac{P_2}{.006}$$

Antilog $-2 + .5 = .0316$ (From tables)

$$.0316 = \frac{P_2}{.006}$$

$$P_2 = .0316 \times .006$$

$$= .00019 = .19 \text{ mw}$$

EXAMPLE 3: Given an input of -19.8 db. Express in milliwatts. This type of problem often causes considerable difficulty because it is customary to treat the decimal part of the db value as a positive mantissa. In this case the .8 is simply the decimal part of 19.8 db and the entire number is considered as being negative, that is, the characteristic is -19.8.

$$\text{db} = 10 \log_{10} \frac{P_2}{.006}$$

$$-19.8 = 10 \log_{10} \frac{P_2}{.006}$$

$$\frac{-19.8}{10} = \log_{10} \frac{P_2}{.006}$$

To make -19.8 divisible by 10 negative .2 must be added to it.

$$\begin{array}{rrr} & -19.8 & + .000 \\ & - \;\; .2 & + .200 \\ \hline 10 \,/ & -20 & + .200 \\ \hline & -2 & + .02 \end{array}$$

$$-2 + .02 = \log_{10} \frac{P_2}{.006}$$

Antilog $-2 + .02 = .01048$

$$P_2 = .01048 \times .006 = .00006288 \text{ w}$$

$$= .0629 \text{ mw}$$

Now suppose it is desired to work in the opposite direction. that is, to convert a given input power level to decibels. Convert .03 mw to db.

$$-\text{db} = 10 \log_{10} \frac{.006}{P_2}$$

$$= 10 \log_{10} \frac{.006}{.00003}$$

$$= 10 \log_{10} 200$$

$$= 10 \; (2.30103)$$

$$= -23.01 \text{ db}$$

For all practical purposes a power of .03 mw represents a power level of -23 db in reference to the arbitrarily selected reference level.

The transmission unit (decibel) can also be used to express the difference between two power levels.

EXAMPLE 5: The input to an amplifier is .7 mw and the output 28 watts. What is the power gain in db?

$$\text{db} = 10 \log_{10} \frac{P_2}{P_1}$$

$$= 10 \log_{10} \frac{28}{.0007}$$

$$= 10 \log_{10} 40{,}000$$

$$= 10 \times 4.602$$

$$= 46.02 \text{ db}$$

The method of proving Example 5 will bring out an interesting point. If .7 mw and 28 w are both converted to db in reference to .006 w the difference between the two db values should be 46 db.

$$db = 10 \log_{10} \frac{.0007}{.006}$$

$$= 10 \log_{10} .1166$$

$$= 10 \times (-1 + .0667)$$

Since the mantissa is always positive the product of $10 \times (-1 + .0667)$ is $-10 + .667 = -9.33$ db. Converting the output 28 watts to db

$$db = 10 \log_{10} \frac{28}{.006}$$

$$= 10 \log_{10} 4,666$$

$$= 10 \times 3.669$$

$$= 36.69 \text{ db}$$

Since .7 mw represents a db level of -9.333 db below the reference level of .006 watt and 28 watts is 36.69 db above that same level, the overall gain will be 9.333 + 36.69 = 46.023 db which agrees with the original answer to Example 5.

EXAMPLE 6: An amplifier has a power gain of 60 db and an output of 15 watts. What is the input power level in db and milliwatts?

$$db = 10 \log_{10} \frac{P_2}{P_1}$$

$$60 = 10 \log_{10} \frac{15}{P_1}$$

$$6 = \log_{10} \frac{15}{P_1}$$

$$\text{Antilog } 6 = 10^6$$

$$10^6 = \frac{15}{P_1}$$

$$P_1 = 15/10^6 = 15 \times 10^{-6}$$

$$= .015 \text{ mw input power level.}$$

$$-db = 10 \log_{10} \frac{.006}{.000015}$$

$$= 10 \log_{10} 400$$

$$= 10 (2.60206)$$

$$= -26.0206 \text{ db input power level}$$

PROOF: $$db = 10 \log_{10} \frac{15}{.006}$$

$$= 10 \log_{10} 2,500$$

$$= 10 \times 3.3979$$

$$= 33.979 \text{ db}$$

Since 15 watts is 33.979 db above zero level and the amplifier has a gain of 60 db, then a signal 60 - 33.979 = 26.021 below zero db will give an output of 15 watts or the amplifier will give an output of 33.979 db with an input signal of -26.021 db.

The decibel can also be used to compare voltage and current levels. Since P varies as E^2 and I^2 ($P = I^2R = E^2/R$) then

$$\text{Voltage gain in db} = 10 \log_{10} \frac{E_2^2}{E_1^2}$$

$$= 10 \times 2 \log_{10} \frac{E_2}{E_1}$$

$$= 20 \log_{10} \frac{E_2}{E_1} \text{ (when } Z_1 = Z_2\text{)}$$

Similarly, current levels can be

expressed in db from the formula

$$\text{Current gain in db} = 20 \log_{10} \frac{I_2}{I_1}$$

$$(\text{when } Z_1 = Z_2)$$

In both of the above formulas the subscript 2 represents the output and subscript 1 the input level.

The gain necessary to raise the power, voltage, or current from one arbitrary level to another *is simply the difference between the two levels in decibels.* Thus, to raise a power input from +2 to +22 db requires an amplifier with a power gain of 22 - 2 or 20 db. If the input level is -10 db and an output of 30 db is desired, the amplifier must have a gain of 30 + 10 or 40 db. In both cases the final db values represent the *power* amplification factor of the amplifier. If the power gain is 20 db, the amplifier would raise an input level of -10 db to +10 db, or an input of -20 db to zero db, etc.

In the design of an amplifier it is often inconvenient to use the power unit (watt) in expressing gain. The volt is much more convenient since the step-up ratios of transformers and the amplification factor of tubes refers to the voltage step-up. The transformer itself gives no power gain. The μ of a tube is the ratio dE_p/dE_g for constant I_p indicating that the amplification factor is a voltage ratio. Thus, voltage gain ratios are frequently used in amplifier design.

TYPICAL AMPLIFIER CALCULATIONS

Audio amplifier design can be divided into two general stages, the preliminary design which deals with the selection of tubes and general circuit components and the final design in which more detailed calculations are made for circuit components, fidelity, etc. This discussion will deal primarily with the preliminary design. More advanced assignments will give formulas and methods for the final stage by stage design. Quite often the preliminary design figures plus a little practical experience is all that is required to design a satisfactory amplifier. By utilizing the information available on tubes and circuits in the tube manual, the design can be greatly simplified.

As explained in an earlier assignment the maximum possible voltage gain that can be obtained from a vacuum tube cannot exceed μ, and the full μ of the tube can be approached only when the load resistance is sufficiently large that R_p may be neglected. Similarly the voltage step-up factor of transformers is not uniform, being true only for one frequency. The step-up ratio of audio transformers is usually expressed for a frequency of 1,000 cycles per second. The efficiency of such transformers is usually quite low, and will drop very rapidly if the current flow in any winding exceeds the manufacturer's rating. Very serious distortion can be introduced by a transformer designed for operation between Class A amplifiers, if grid current is permitted to flow in the transformer secondary. If the normal tube plate current flowing through the primary of the transformer is increased, the transformer core may tend to saturate on signal peaks introducing considerable distortion into the signal.

In preliminary design it is customary to assume an average efficiency for an audio transformer of about 90 per cent for voltage gain. In selecting a transformer the following factors must be considered: the primary impedance (usually measured at 1,000 c.p.s.) since that factor will be used in determining the voltage gain of the preceding tube; the normal primary current that will permit the transformer to work well below d.c. saturation; and the turns ratio. In preliminary design work the voltage step-up ratio is usually taken as ninety per cent of the turns ratio.

From the above it is apparent that the preliminary design of an amplifier is only a rough approximation. Sufficient additional gain is usually provided to allow for unpredictable losses that are not considered in the early design.

Consider the amplifier in Fig. 1. The gain can be calculated as 20 log E_2/E_1, if the input and output impedances are equal. If these impedances are not equal, a correction factor may be used to arrive at the actual gain. If the output impedance is 2,500 ohms (value give in the tube manual for a single 2A3 tube), and the input impedance is a 500 ohm line, then the correction factor will be

$$10 \log \frac{Z_1}{Z_2} = 10 \log \frac{500}{2500} = 10 \log .2$$

$$= 10\ (-1 + .302) \cong -7 \text{ db}$$

Since T_2 is working into a Class A 2A3 stage which is drawing no grid current from the secondary, the primary impedance is essentially X_L. At 100 c.p.s. X_L should be at least 3 R_p, or 30,000 ohms, and at 1,000 c.p.s. it will therefore be ten times as great, or 300,000 ohms.

The gain of the 6C5 stage at 100 c.p.s. for a μ of 20 and R_p of 10,000 ohms will be

$$\alpha_{100} = \frac{\mu X_L}{\sqrt{(R_p)^2 + (X_L)^2}}$$

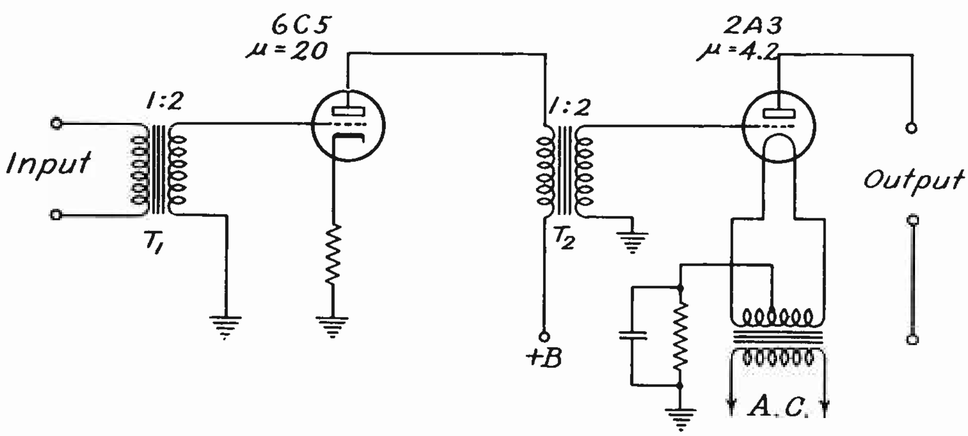

Fig. 1.--Two Stage Amplifier

$$= \frac{20\,(30000)}{\sqrt{(10000)^2 + (30000)^2}}$$

$$= \frac{6 \times 10^5}{\sqrt{10^9}} = 18.95$$

or 0.948 μ.

A similar calculation for the gain at 1,000 c.p.s. will yield the value $\alpha_{1000} \cong 20.0$. This indicates that over the useful frequency range the gain is fairly constant at the value of μ for the tube.

The gain of the 2A3 stage is found from $\dfrac{\mu Z_L}{R_p + Z_L}$ where R_p is 800 ohms, μ is 4.2, Z_L is essentially resistive, and of a value of 2,500 ohms. This has been discussed in a previous assignment dealing with power amplifier stages. Substituting

$$\alpha = \frac{4.2 \times 2500}{800 + 2500} = 3.18$$

This can be checked from the load line for 2,500 ohms and -43.5 volts bias on the 2A3 curves in the Tube Manual. A plate swing of 105 to 366 gives a total of 261 volts peak to peak voltage. Divided by twice 43.5 or 87 volts grid swing,

$$\alpha = \frac{261}{87} = 3.00$$

The two methods check closely although the latter method is preferable for accuracy in all applications for a power amplifier stage.

The total gain at 100 c.p.s. will be found as follows,

$$.9(2) \times 18.95 \times .9(2) \times 3.00 = 184.2$$

in db the gain is,

$$20 \log 184.2 + 10 \log \frac{500}{2500}$$

$$= 20\,(2.2653) - 7 = 45.3 - 7 = 38.3 \text{ db}$$

If a high mu tube such as a 6K5 tube with an R_p of 50,000 ohms and a μ of 70 is used, the gain at 100 c.p.s. will be increased, using the same transformer T_2, as follows:

$$\frac{70\,(30000)}{\sqrt{(50000)^2 + (30000)^2}} = \frac{2100000}{\sqrt{34 \times 10^8}}$$

$$\frac{21 \times 10^5}{5.84 \times 10^4} = 36$$

the db increase in gain is given by

$$20 \log \frac{36}{18.95} = 20 \log 1.897$$

$$= 20\,(.27807) = 5.56 \text{ db}$$

The total gain at 100 c.p.s. would be 38.3 plus 5.56 or 43.9 db. However, at 100 c.p.s. the gain relative to that at 1,000 c.p.s. will not be in the same proportion for the two tubes. The frequency response will be quite different, which is an important factor in audio amplifiers, and the extra gain is unimportant in comparison for most applications, since fidelity or uniform response is more desirable.

At 1,000 c.p.s. the gain of the 6C5 stage was found to be practically 20. A similar calculation at 1,000 c.p.s. for the 6K5 yields a value of practically 70, and the db increase in gain is 10 log (70/20) = 20 (.5441) = 10.88 db. Thus, if a 6K5 tube were substituted for the 6C5 tube, the gain would be increased, but unfortunately only 5.56 db at 100 c.p.s. and 10.88 db at 10,000 c.p.s. Since the gain using a 6C5 tube is practically flat over the frequency range, this means that the gain will have a *rising* characteristic from 100 to 1,000 c.p.s., when a 6K5 tube is used, or to put it another way, the low frequencies, such as 100 c.p.s. will be attenuated relative to the higher frequencies. Hence, in spite of its lower gain, the 6C5 tube is preferable to the 6K5 tube for a transformer-coupled stage.

The average plate swing of the output tube, such as the value 261 given previously for the peak-to-peak value, divided by two is 261/2 = 130.5 volts peak value. The input voltage needed can be found by dividing this voltage by the amplifier gain to determine the peak input voltage.

$$\frac{130}{184.2} = .706 \text{ volts peak}$$

This is the value needed for the gain of 184.2 found for one case previously. Knowing the input voltage and output power the amplifier design is well under way and it is easily seen whether it will meet requirements.

Suppose it is desired to double the power output of the amplifier shown in Fig. 1. Another Type 2A3 tube can be connected in parallel with the original tube or a push-pull amplifier can be used in the power stage. No additional voltage gain will be obtained from the parallel combination and the excitation voltage will still remain approximately 45 volts peak. Placing two tubes in parallel will necessitate halving the load resistance but for the same excitation the current variation in the load will be doubled. $2I \times .5R = IR$ where I is the a.c. component of current developed by one tube, and R is the normal load resistance for one tube. Power output is I^2R or $(2I)^2 \times .5R = 4I^2 \times .5R = 2I^2R$ or double. With 7 watts output the power level is

$$\text{db} = 10 \log \frac{7}{.006}$$

$$= 10 \log 1{,}167$$

$$= 10 \times 3.07$$

$$= 30.7 \text{ db for the first case}$$

$$= 10 \log \frac{3.5}{.006}$$

$$= 10 \log 583$$

$$= 10(2.77) = 27.7 \text{ db}$$

Doubling the power output allowed only a 3 db increase, an amount that would just be noticed by the ear. However, this slightly higher power gain will allow a lower input power level for the same output.

Parallel operation of audio amplifier stages has two principal

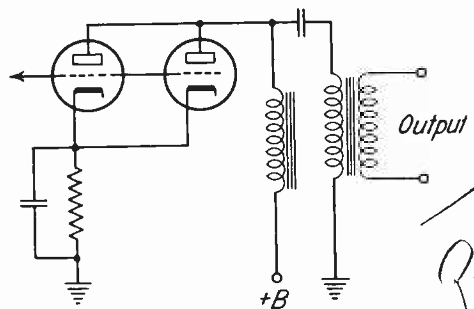

Fig. 2.--Parallel output stage.

disadvantages: the harmonic distortion is double that produced by one tube and the increased plate current through the output transformer primary may be sufficient to cause core saturation unless a large well designed transformer is used. This second disadvantage may be avoided by using parallel feed to the plates through a large audio choke as shown in Fig. 2. A high inductance-high current choke is a comparatively expensive item, and since push-pull operation possesses several decided advantages, parallel operation of audio amplifier tubes is rarely used.

PUSH-PULL AUDIO AMPLIFIERS

The principal advantages of push-pull operation are an output somewhat greater than that obtainable from two tubes in parallel, cancellation of all even order harmonics, and elimination of danger of core saturation in the output transformer. Fig. 3 shows the circuit of Fig. 1 arranged for push-pull

1 to 1.5 in each half of the secondary or $N_p/.5N_s = 1/1.5$. The overall ratio would then be 1 to 3.

The voltage gain of a push-pull Class A stage is twice that of a single tube. This is because both tubes are essentially in series with the load and the voltage developed across one-half the primary of the output transformer by one tube is in such polarity as to add to the voltage developed by the other tube across the other half of the primary. For Class B amplifiers this additional voltage gain is not obtained since only one tube is considered to be working at a time. Class AB_2 amplifiers are treated as Class B amplifiers in

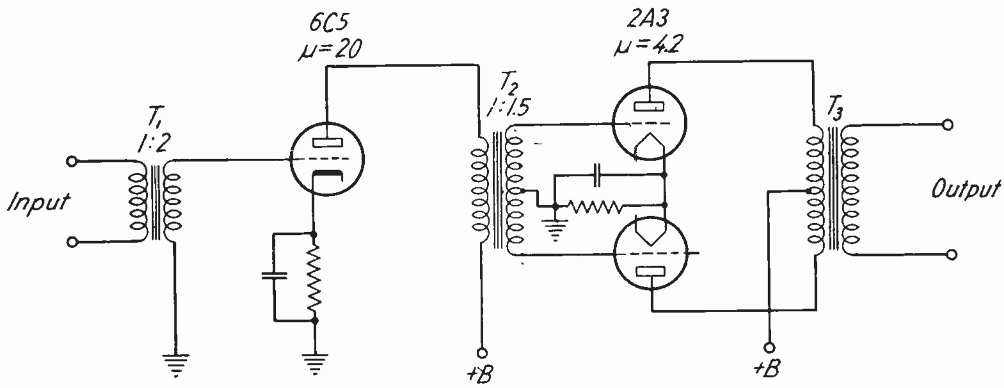

Fig. 3.--Two stage push-pull output amplifier.

operation of the output stage. Push-pull input and output transformers have been substituted for the single stage transformers used in Fig. 1. Such transformers are usually rated in accordance with the turns ratio of one-half the secondary to the entire primary. Thus, a push-pull transformer with a 1 to 1.5 step-up ratio refers to a step-up of

preliminary design calculations.

The power output of a push-pull stage is usually somewhat greater than twice that obtained from a single tube as will be explained later in this assignment. For practical purposes the power output may be taken as twice that of one tube. Assuming an output of 7 watts for the amplifier of Fig. 3, the power output level of the amplifier will be approximately 31 db. If an efficiency of 90 per cent is taken for the transformers and using the gain previously calculated for the tubes, the approximate voltage gain will be:

$$.9(2) \times 20 \times (1.5).9 \times 2 \times 3$$

$$= 291 \text{ at } 1{,}000 \text{ c.p.s.}$$

The greater voltage gain of the push-pull amplifier will of course permit full output to be obtained from an input signal much lower in level than is needed for the single-ended amplifier of Fig. 1.

If an output of 50 watts is desired, an additional push-pull stage using Type 845 tubes can be added to the amplifier of Fig. 3. Using a 1:1 input transformer, a voltage gain of approximately 6 could be expected from this additional stage. The power output level would then be 39 db and the voltage gain approximately 6 × 291 = 1,746.

A comparison of the 50-watt push-pull amplifier and the push-pull 2A3 amplifier of Fig. 3 will bring out some interesting points. The 2A3 push-pull amplifier has a power output level of 31 db and a voltage gain of 291. It requires an input voltage of 184/291 or 0.632 that of the single 2A3 amplifier. The 50-watt amplifier requires 184/1,746 or 0.1054 the input voltage of the single 2A3 amplifier. These values are based on equal input and output impedances. This shows that increased output with a lower input voltage is possible using the same gain in the 6C5 stage.

The gain of the 50-watt amplifier is sufficient to permit operation direct from a phonograph pick-up but is not quite enough to permit operation direct from the average microphone. If microphone input is to be used, a pre-amplifier with an approximate voltage gain of 30 db would be required.

$$30 = 20 \log E_2/E_1$$

$$1.5 = \log E_2/E_1$$

$E_2/E_1 = 31.63$ or 32 *(for equal input and output impedance).*

A voltage gain of 32 is easily obtained from another 6C5 stage with a 1 to 3 or 1 to 4 input transformer.

For an inexpensive radio receiver where a fairly large power output with a minimum number of tubes and a simple circuit is desired, the power amplifier pentode is very practical. The type 6F6 has an amplification factor of 200 and a power output of 3 watts with a plate potential of 250 volts. With a 7,000-ohm load a voltage gain of approximately 20 can be obtained. Using two 6F6 tubes in push-pull with a 1 to 1.5 step-up transformer, a total voltage gain of approximately 60 can be obtained. This is a gain of 20 log 60 = 20(1.78) = 35.6 or 36 db for equal impedances. A power output of 6 watts is easily obtained from the push-pull combination with a plate voltage of 250. Six watts corresponds to a power level of 30 db. With a power output of 30 db and a voltage gain of 36 db, the input signal level may be down as much as -6 db for full output. This is easily within the range of the output of a power detector. It should be noted that although the output of the push-pull 2A3 amplifier is one watt greater than that of the push-pull 6F6 amplifier, the actual difference in power levels is only .7 db. So far as actual volume is concerned, there is little choice between the two amplifiers. However, the use of the 6F6 tubes with their high amplification factor permits the elimination of the first audio stage, a considerable help where economy and space are important factors. Pentodes are more prone to third harmonic distortion than triodes so that is also a factor to be considered.

From the foregoing it will be seen that the preliminary design of an audio amplifier involves only a few simple calculations and a large portion of common sense. Where resistance coupling is used the actual gain per stage for various tube voltages and circuit values can be taken directly from resistance amplifier charts in the tube manual. Familiarity with the various tubes commonly used in audio amplifiers will be a great help.

PUSH-PULL AMPLIFICATION

In most audio amplifiers, where large power output and high quality reproduction are required, a push-pull circuit is used. This type of circuit is also used extensively in radio frequency power amplifiers. Because of its wide application a thorough understanding of the theory of the push-pull amplifier is desirable.

Fig. 4 shows a schematic diagram of a push-pull amplifier. First, consider the circuit from the d.c. standpoint. Grid bias is applied to the grids through the center tap of the input transformer T_1. If the two tubes are well matched, they will be adjusted to the same operating point on their $E_g I_p$ curves and identical plate currents will be obtained. Since the plate voltage is applied to the tubes through the center tap connection of the primary of the output transformer the normal plate current of the two tubes will *flow in opposite direction in the primary* and the magnetomotive force due to this current will be essentially zero. Under these conditions there will be no magnetic field set up in the core of the transformer. In the single-ended stage the normal d.c. plate current maintains a constant flux density in the core and care must be taken to insure that the core does not saturate during the peak excursions of plate current. In the push-pull output transformer

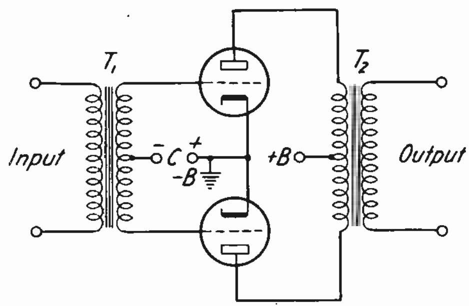

Fig. 4.--Push-pull amplifier.

this steady magnetization is not present and hence a high permeability core may be used which allows the necessary primary inductance to be obtained with a minimum number of primary turns. A high permeability core will saturate under a small magnetizing force so it is very desirable that

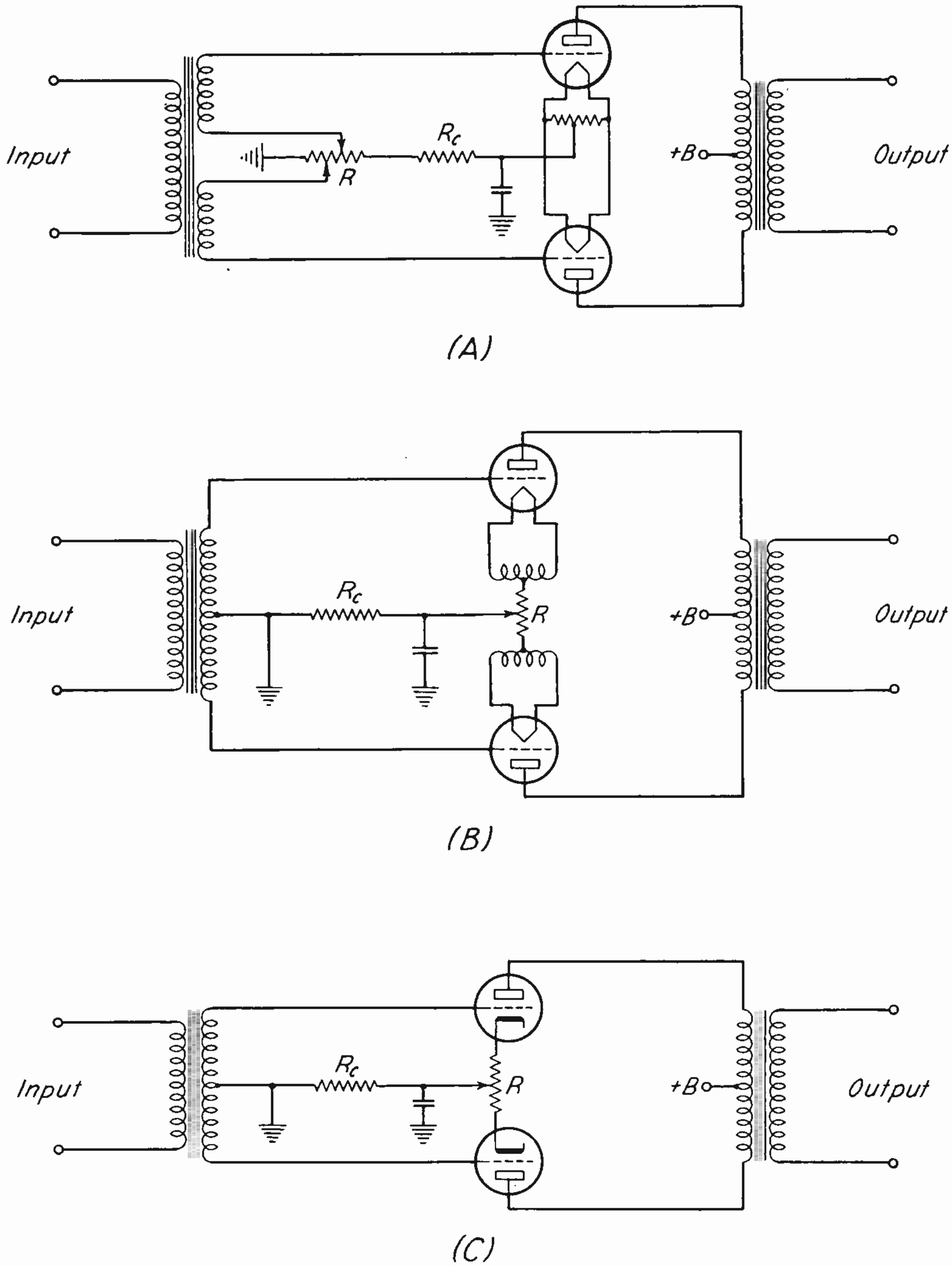

Fig. 5.--Various bias circuits for push-pull amplifiers.

tubes selected for use in a push-pull amplifier have identical plate currents for the same grid bias. When high transconductance tubes are used in the amplifier, it is best to use a split secondary input transformer so that the bias on each tube can be adjusted independently for identical plate currents. Fig. 5 shows three methods commonly used to obtain balanced plate currents.. In Fig. 5(A) a split secondary is required on the input transformer. In (B) two separate filament heater windings are required. (C) is similar to (B) except that heater type tubes are used and hence separate heater windings are not required. R in each circuit should be approximately ten per cent of the total cathode resistance required. By keeping R as small as practical only one by-pass condenser connected across R_c is necessary. When fixed bias is used, a split secondary on the input transformer will permit individual biasing of each tube.

Now consider the push-pull circuit from the a.c. viewpoint. With an excitation voltage applied to the primary of the input transformer the voltage applied to the two grids will be 180 degrees out of phase because the grids are connected to opposite ends of the transformer secondary. If the voltage on grid one is swinging in a less negative direction, that on grid two will be swinging more negative. Plate current will vary in phase with E_g so that the a.c. voltage component across one-half of the output transformer primary will be increasing above normal while the voltage across the opposite half is dropping below normal. *The a.c. component of voltage across the entire primary of the output transformer will be the sum of the voltage drops across each half.* For example, with a normal plate voltage of 250 volts, if the excitation applied to the grid of one tube increases I_p so that the voltage across one-half the output primary rises 10 volts, then the voltage applied to grid two will be of opposite polarity, and if the tubes are well matched, the plate current in tube two will decrease enough to decrease the voltage across the second half of the primary by an equal amount. If the voltage at one end of the primary rises ten volts, while that at the other end drops ten volts, the actual potential difference between opposite ends of the primary will be 10 + 10 = 20 volts.

Thus, the voltage developed across the entire primary will be twice that produced by a single tube working into one-half the primary. Therefore, the theoretical voltage gain of a push-pull amplifier is twice that of a single tube. This is true for the same excitation voltage per tube in either case. That is, the primary to all the secondary for a single tube, is the same turns ratio as the primary to 1/2 the secondary in the push-pull amplifier.

Since the output voltages of the tubes add across the load the tubes are equivalent to two alternators connected in series and in phase as shown in Fig. 6. Consider the conditions that exist in this circuit for the voltages shown when switch Sw is open. The voltage E_1 generated by alternator 1 is applied across N_1. If E_1 = 100 volts and E_s is 10 volts, the step down ratio of the transformer (N_1/N_s) is

100/10 or 10 to 1. The current in R_L is E/R = 10/1 = 10 amperes. The power output is I^2R or $10^2 \times 1$ = 100 watts. Neglecting transformer losses, the current through alternator 1 is P_o/E = 100/100 = 1 ampere. The effective primary impedance of N_1 is E/I = 100/1 = 100 ohms.

In an earlier assignment it was shown that the turns ratio of a

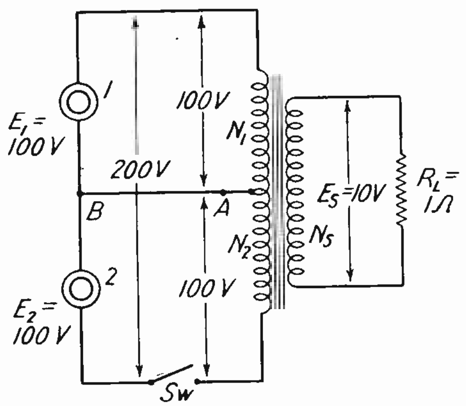

Fig. 6.--Equivalent push-pull circuit.

transformer to work between two known resistances was given by the equation

$$N_p/N_s = \sqrt{R_p/R_s}$$

or

$$N_p^2/N_s^2 = R_p/R_s$$

from which

$$R_p = (N_p/N_s)^2 R_s \qquad (1)$$

where R_p is the impedance of N_1. When the switch Sw is open in Fig. 6

$$R_p = (10/1)^2 1 = 100 \text{ ohms}$$

Therefore, alternator 1 is working into a load resistance of 100 ohms when switch Sw is open.

When switch Sw is closed, this condition no longer holds true. If $N_1 = N_2$, points A and B are at the same potential and no alternating component of plate current will flow in the center tap lead AB. The current due to alternator 1 must return through alternator 2 and the two alternators are effectively in series. Since $N_1 = N_2$, then $N_p = 2N_1$. Doubling the turns of the primary will double the turns ratio of the transformer N_p/N_s. But the voltage across the primary is now $E_1 + E_2$ = 200 volts, just double the value obtained with the switch Sw open. Doubling the primary voltage and halving the turns ratio will maintain E_s at its original value of 10 volts. The secondary current will remain at 10 amperes and the power output will still be 100 watts. With 200 volts across the primary and a power output of 100 watts, the primary current is now

$$P_o/E_p = 100/200 = .5 \text{ ampere}$$

The power delivered by each alternator is EI or 100 × .5 = 50-watts. The impedance of N_1 is now 100/.5 = 200 ohms. *Connecting alternator 2 in the circuit has the effect of doubling the impedance into which each alternator works. This reduces the power output of alternator 1 to one-half its original value. This rise in the effective impedance into which each alternator works is caused by the coupling or mutual inductance which exists between N_1 and N_2.*

It should be noted that the total resistance looking into N_p is 200/.5 or 400 ohms, which is

4 times the resistance looking into N_1 alone. This also follows from the rule that inductance varies as the square of the number of turns. If $N_1 = N_2$, when switch Sw is closed, the primary turns are doubled multiplying the inductance and inductive reactance by a factor of 4.

If the two alternators are to produce twice the power output of one tube, it is necessary to *reduce* the load resistance to one-half that used for one tube. In an earlier assignment it was explained that maximum power output from any generator is obtained when $R_p = R_L$, but maximum undistorted power output is obtained from a vacuum tube when R_L is approximately equal to $2R_p$. In the push-pull amplifier R_L can be reduced until the amplifier is working into a load only slightly greater than R_p without distortion exceeding the usual limits. It is this permissible reduction in R_L which permits the power output of a push-pull amplifier to be greater than twice the power output of a single tube. The statement is often made that the output of a push-pull amplifier is more than double that of a single stage because the tubes can be pushed harder. The error of this statement is seen in the preceding explanation.

DISTORTION IN PUSH-PULL AMPLIFIERS

As explained in earlier assignments a certain amount of amplitude distortion can be expected in any amplifier because of the curvature in the characteristic curves. A large value of load resistance will make the characteristic more linear but this results in a decrease in output. The predominating harmonic in a triode amplifier is the second, the third harmonic being quite small unless the tube is pushed to extremes. It has been stated previously that the second harmonic distortion in a push-pull amplifier is cancelled out and hence, with triode tubes the total distortion will be almost negligible if the tubes are well balanced and operated in the proper manner.

The alternating voltages developed across the two halves of the output transformer are in phase although the d.c. voltage drops are in phase opposition. With no signal impressed on the grids of the tubes, the effective magnetomotive force in the transformer is zero since the d.c. plate currents flow in opposite directions through the primary. With a signal voltage on the grids the magnetomotive force acting in the transformer is equivalent to that produced by a current equal to the difference between the plate current flowing in tube 1 and the current flowing in tube 2. At zero signal $I_{p1} = I_{p2}$ and the a.c. component of $I_p = 0$. If at some instant I_{p1} is 20 ma and I_{p2} is 30 ma, the effective I_p in the entire primary of the transformer is 30 - 20 = 10 ma. This is shown in Fig. 7. The E_gI_p curves of two tubes are so drawn that one set is inverted, that is, E_g increases in a negative direction from left to right instead of right to left as in the case for the upper set of curves. The resultant curve is obtained by noting the plate current of each tube for corresponding values of E_g and *plotting the difference between those plate currents*. If the two E_gI_p curves are identical, the resultant curve will be a straight line. The amount of deviation from a straight line depends on the difference in the E_gI_p curves although the resultant will always be straighter than either curve considered individually.

Study of Fig. 7 will show why the second harmonic distortion cancels in a push-pull amplifier. An earlier assignment explained how the second harmonic was caused by curvature at the upper and lower limits of the linear portion of the E_gI_p curve. Operating into this curvature causes I_p to vary more in one direction from normal than in the other.

In Fig. 7 the resultant characteristic is practically a straight line indicating the amplification factor is constant over the entire operating range and, thus second harmonic distortion is practically eliminated. This is shown also in the individual plate current curves of Fig. 7. The plate current in tube 1 tends to vary more above normal than below normal resulting in positive rectification, that is, the operating point tends to shift upward on the E_gI_p curve. In tube 2 this same condition exists but since the tubes are working back to back, the tendency for the operating point to shift is cancelled. If both tubes are well balanced and not over-excited second harmonic distortion will be practically zero. However, over-excitation may cause even order harmonics to appear since the E_gI_p curves of both tubes will rarely be identical in the vicinity of saturation. Even harmonic cancellation in a push-pull amplifier is dependent on both tubes producing the same amount of distortion.

Third harmonic distortion is not cancelled in a push-pull amplifier. This type of distortion is due to curvature in the so-called straight portion of the E_gI_p curves. This causes the resultant characteristic to deviate from a straight line. Ordinarily third harmonic distortion is all that is considered in push-pull amplifier operation, but if the amplifier is over-excited considerable fifth harmonic distortion may appear in the output.

Pentodes, because of their high third harmonic distortion, have few advantages when used in push-pull circuits. The third harmonic distortion of a push-pull pentode amplifier will be approximately twice that introduced by a single tube, and quite often it is necessary to reduce the excitation in order to restrict the distortion to the customary 5 per cent limit. This, of course, reduces the power output and may offset the original advantage of high gain. However, the development of "degenerative feedback" has provided a means of reducing all harmonics, odd and even. This subject will be discussed in detail in a later assignment. Briefly, it consists of feeding back into the grid circuit a part of the plate output voltage, in such polarity that inverse distortion voltages are deliberately introduced at the grid to neutralize the distortion developed in the amplifier itself. This makes it possible to use pentodes and beam type power amplifiers in push-pull for the development of large audio power with comparatively small tubes.

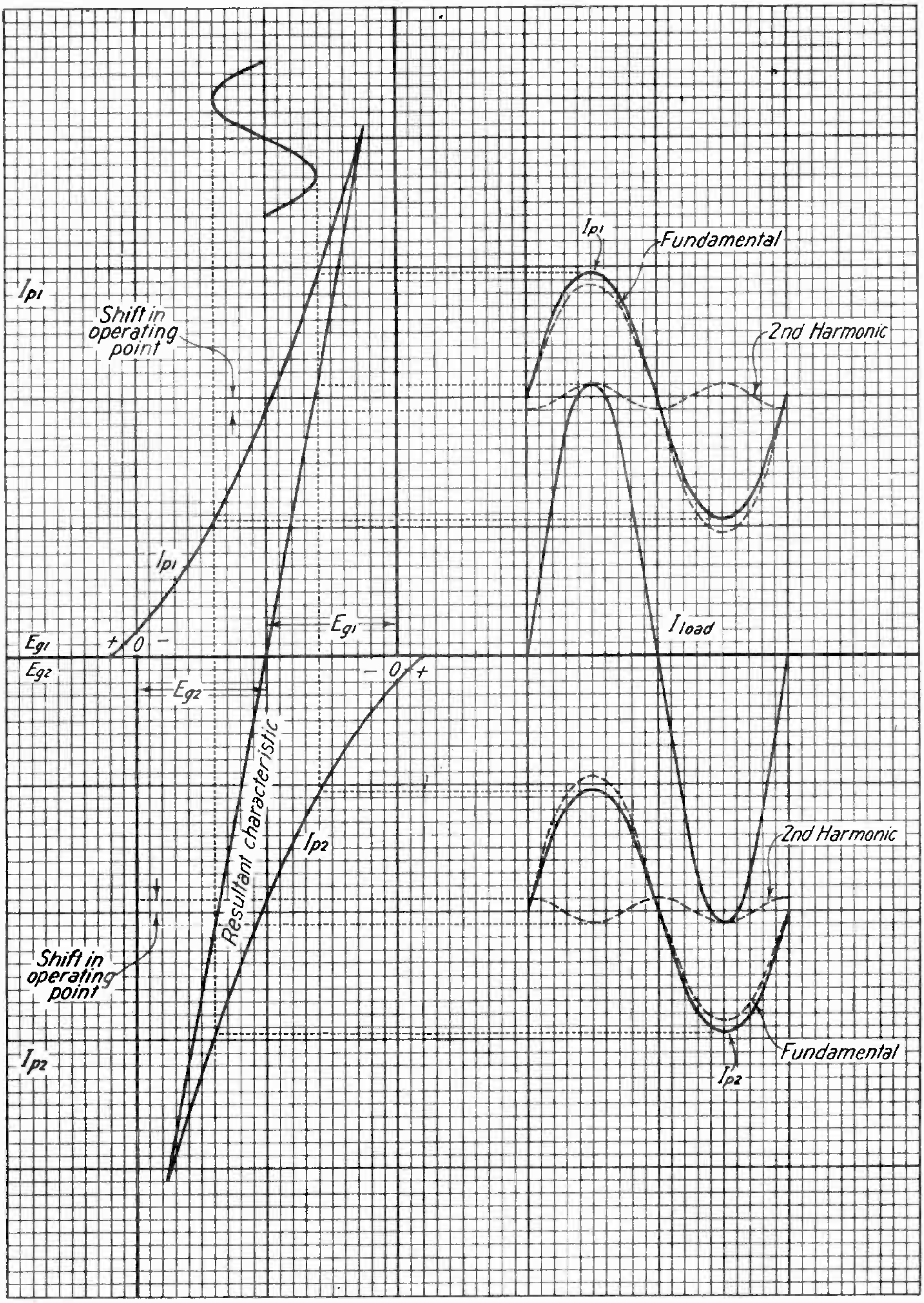

Fig. 7.--Push-pull Tube Characteristics.

CLASS B AUDIO AMPLIFIERS

Where large audio power output is desired from relatively small tubes, the tubes may be operated as Class B amplifiers in push-pull. In the study of radio frequency Class B amplifiers where the plate load consists of a tuned circuit, it was shown that the plate voltage will make two practically identical variations, above and below normal d.c. plate voltage, and very little distortion will result. At audio frequencies the "flywheel effect" of the tuned output circuit is not present: sinusoidal output for sinusoidal input will exist only during one-half of the excitation cycle, the half in which the grid excitation is swinging in a positive direction. However, if two tubes are connected in a push-pull circuit so that each tube works on one-half of the input cycle, the combined output will have practically the same form as that of the input.

In a Class A amplifier plate current flows at all times, and if operated so as to minimize non-linear distortion, the grid cannot be permitted to swing positive. This definitely limits the power output and the operating efficiency. The power output of a Class A amplifier with sinusoidal input is equal to:

$$P_o = .707\ E_o \times .707\ I_o = .5\ E_o I_o$$

in which E_o is the maximum plate voltage *variation*, and I_o is the maximum plate current *variation*. The power input is:

$$P_{in} = E_b I_b$$

where E_b is the d.c. plate voltage and I_b is the plate current taken from the power supply. The operating efficiency is:

$$\text{Efficiency} = \frac{.5 E_o I_o}{E_b\ I_b}$$

As E_o approaches E_b as a limit, and as I_o approaches I_b as a limit, the maximum efficiency, if the output maintains a sine wave form, is 50 per cent. Since practically the plate current and plate voltage cannot vary over such wide limits without the grid swinging positive or into the lower bend of the $E_g I_p$ curve, this efficiency cannot be obtained, *the usual maximum efficiency for undistorted output being about 20 per cent.*

In the case of the Class B amplifier, the tube is biased so that with no excitation the plate current is essentially zero and is zero on the negative swings of the excitation voltage. On the positive excitation swing the peak plate current is limited only by the emission, the load resistance, and the plate voltage, and the plate current is essentially proportional to the instantaneous value of the grid voltage on the positive swings. This means that in the case of the Class B amplifier, the grid may be permitted to swing as far positive as the straight portion of the $E_g I_p$ curve will permit without the introduction of distortion *so long as the source of excitation power is sufficiently great to keep the excitation voltage in its original form, even when the grid takes current and the input impedance drops.*

So long as the grid is negative there is no grid current and the input impedance is high, thus, very little power is required to vary the grid voltage, but when the grid swings positive, grid current flows, the input impedance drops rapidly, and considerable power is required to effect a change in grid voltage. The driving amplifier must be capable of supplying this varying excitation power without substantial change in the form of the excitation voltage.

So long as the plate current is sinusoidal, the current input to the two tubes resembles that of a full-wave rectifier. The total average input current is $.636\ I_o$, and the power input is $.636\ I_oE_b$. The power output from *one tube* operating Class B is:

$$P_o = \frac{.707\ E_o \cdot .707\ I_o}{2} = \frac{.5\ E_oI_o}{2}$$

It will be seen that this is one-half the output of one tube operating Class A with equivalent E_p and I_p variations. For two tubes operating Class B in push-pull the output will be doubled or:

$$P_o = \frac{2 \cdot .5\ E_oI_o}{2} = \frac{E_oI_o}{2} = .5\ E_oI_o$$

Since the load resistance, R_L, is equal to E_o/I_o and E_o is equal to I_oR_L then

$$P_o = \frac{I_o^2R_L}{2}$$

$$P_{in} = .636\ I_oE_b$$

$$\text{Efficiency} = \frac{I_o^2R_L}{2} \div .636\ I_oE_b$$

$$= \frac{I_o^2R_L}{1.272\ I_oE_b}$$

If $E_o = E_b$ then

$$P_o = .5\ E_oI_o$$

and

$$\text{Efficiency} = \frac{.5\ E_oI_o}{.636\ E_oI_o} = \frac{1}{1.272}$$

$$= 78.5 \text{ per cent}$$

It is thus shown that the ~~the~~ efficiency of the Class B amplifier with sinusoidal output, as E_o approaches E_b as a limit, becomes 78.5 per cent for either half-wave output from one tube or for full-wave output from two tubes, both the input and output being doubled in the latter condition if all other conditions remain unchanged. Since the power output that can be obtained from a tube is limited only by the peak plate power dissipation or the emission, and since the efficiency of the Class B amplifier is so high, a tube operated in this manner can deliver 3 to 10 times as much power as when operated as a Class A amplifier. For example, two Type 6L6 tubes operated Class A in a push-pull amplifier with fixed bias will deliver a maximum output of 17.5 watts with 270 volts on plate and screen. The same tubes operated Class AB_2 with 360 volts on the plate and 270 volts on the screen will deliver 47 watts output. Under this latter condition the peak instantaneous grid power will be about .27 watt. Allowing for circuit losses and not overworking the preceding amplifier, one Type 6F6 triode-connected operating as a Class A amplifier will drive the 6L6 tubes in the Class AB_2 arrangement.

Reference is made above to Class AB operation while discussing Class B amplifiers. As its name implies, the Class AB amplifier is a compromise between Class A and Class B. The Class AB amplifier is biased more negatively than Class A but not to cut-off as for Class B. Two methods of operation are used: Class AB_1 in which the excitation is not permitted to drive the grid positive, in which case the operating conditions are very similar to Class A; and Class AB_2 in which the excitation is allowed to drive the grid positive, in which case the operating conditions approach those of Class B.

Class B audio amplifiers are not used extensively in the average home broadcast receivers for several reasons. Power in excess of 20 watts is rarely required in such receivers, and sufficient power can usually be obtained from an amplifier operated Class AB. As will be explained later, a Class B amplifier requires very carefully designed input and output transformers as well as a power supply having excellent regulation if distortion is to be held to a minimum. A practical example of the use of Class B push-pull audio amplification is in broadcast receivers designed for battery operation on farms and other sections where power from a lighting circuit is not available. In order to obtain a power output comparable to that of the modern a.c. operated receivers, the drain on B batteries with Class A amplification would be excessive. With a Class B amplifier the normal plate current is very low during idle periods and varies with excitation so that a much longer life may be expected from the B batteries. Quite large outputs may be obtained at low plate voltages as indicated by the Type 1J6-G tube which delivers 2 watts output with only 135 volts plate potential. This tube consists of two Class B triodes in one envelope and requires a filament current of .24 ampere.

DISTORTION IN CLASS B AND AB AMPLIFIERS

If the proper load impedance and tube voltages are used and the tubes are well matched, even order harmonics are cancelled in a push-pull Class B amplifier. In Fig. 8 if tube 1 and tube 2 are biased to operate at points a and b respectively, then for small signal voltages the amplifier operates Class A and the resultant characteristic between these points is a straight line. If the tubes are well matched, the entire characteristic will be very nearly straight and even order harmonics will be essentially zero. However, in practice, it is difficult to match tubes exactly so some second harmonic distortion can usually be expected. Third harmonic distortion is in general much higher in Class B amplifiers than in Class A particularly if the amplifier is driven to near maximum output. This is due to the departure of the characteristic of the tubes from a straight line and also to transformer deficiencies. As mentioned earlier, the design of input and output transformers for Class B amplifiers is quite critical.

3rd harmonic A + B

Fig. 9 shows a typical Class B amplifier with its associated driving stage. The resistance R_L as presented to the tube during its operating half-cycle is the resistance of R_L as viewed when looking into one-half the primary; that is, the ratio of transformation

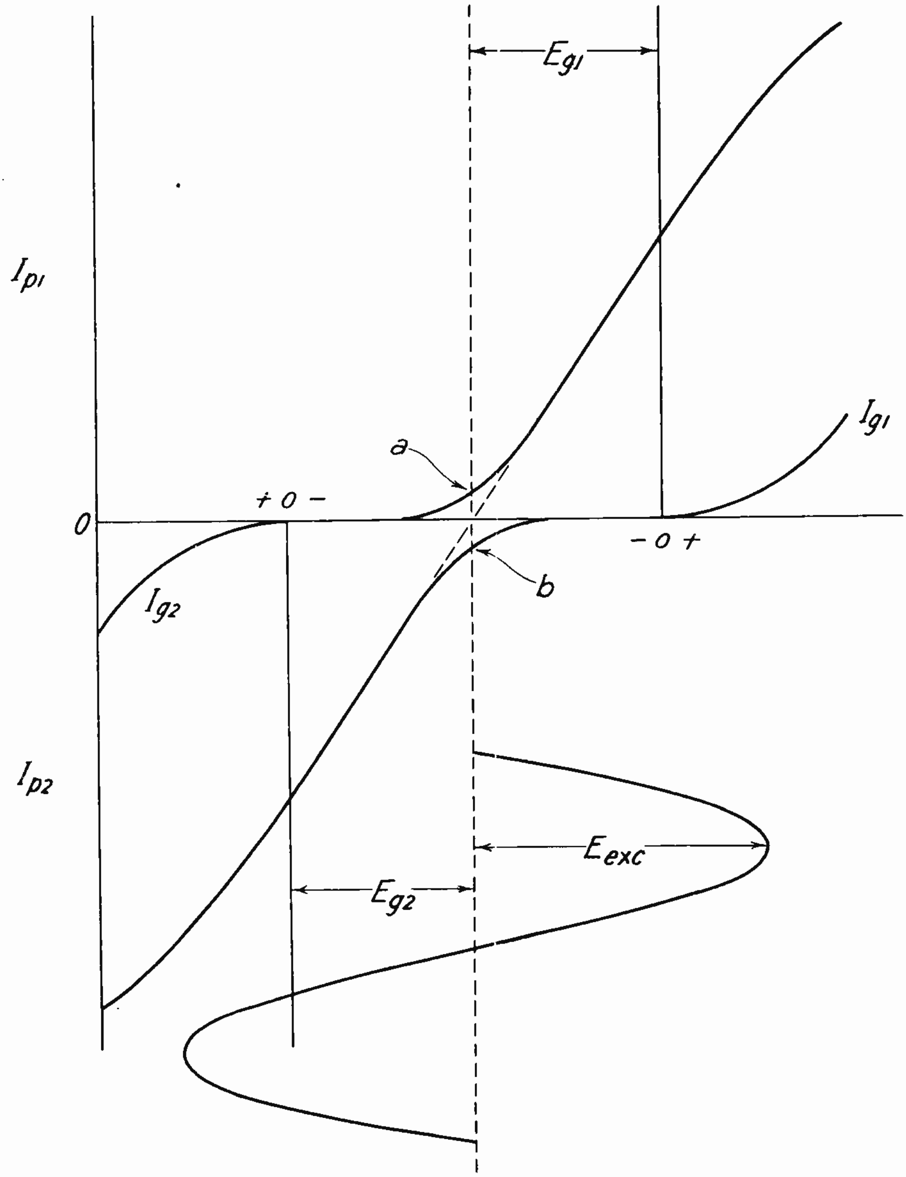

Fig. 8.--Push-pull characteristic curves.

in the output transformer is $N_s/.5N_p$. In other words, each tube works into a resistance equal to $(.5N_p/N_s)^2 \times R_L$. Because plate current flows in only one-half of the primary at time and may reach quite high peak values, the transformer core must be well designed if distortion due to saturation is to be avoided. The primary must be well balanced having an equal number of turns and identical resistance in each half if distortion is to be held to a minimum. The two halves of the sine wave as produced by the tubes are combined in the transformer primary and any unbalanced condition in that winding will introduce distortion.

As explained previously, the maximum power output of a push-pull amplifier is obtained only when the grids are swung positive during the excitation cycle, which means that grid current will flow and the input impedance will drop. This would not be so bad if the drop in input impedance were linear, but the grid current curve has the general shape of an $E_g I_p$ curve so that for small values of I_g the input impedance will change slowly, but when I_g passes the lower knee of the $E_g I_g$ curve a small change in E_g causes a large change in I_g, and hence a large change in input impedance. Thus, the driver is working into an impedance that may not only vary over very wide limits, but also may vary quite abruptly at certain points in the excitation cycle. Therefore, the excitation cycle may be distorted at the tube input if the driver is incapable of maintaining distortionless output under the varying load. There are three methods of minimizing this distortion. If the Class B

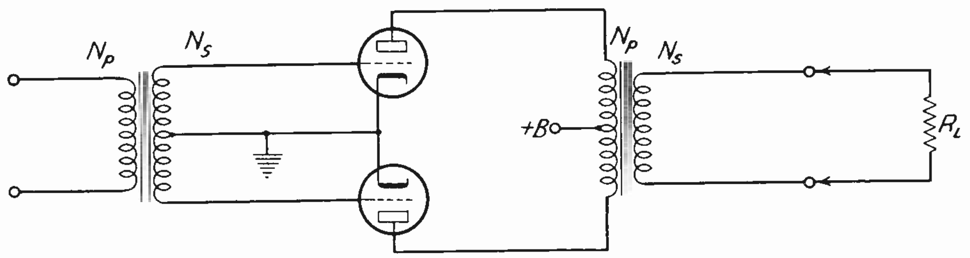

Fig. 9.--Push-pull Class B stage.

amplifier tubes are operated at the zero bias point, then grid current will flow continuously throughout the excitation cycle and the input impedance will not vary over such wide limits. The second method necessitates using a low-impedance driver so that variations in load will not affect the output to a marked degree. Since the input transformer alternately furnishes power to first one grid and then the other, the effective ratio of transformation is $.5N_s/N_p$, just the opposite to that for the output transformer. By using a low-impedance driver a high-load impedance can be presented to the driver tube without using an excessive step-down ratio. As explained in an earlier assignment, a high-load impedance tends to reduce distortion although power output is reduced at the same time. Allowance should be made for transformer losses when computing the output of the driver stage. The average efficiency will be in the order of 90 per cent on a voltage gain basis as mentioned previously.

The third method of reducing distortion in the input to the Class B amplifier is to use high μ tubes in the amplifier. In that case only a small excitation voltage will be necessary to drive the amplifier to full output and a greater step-down ratio is permissible in the input transformer. This will permit the driver tube to work into a load impedance well above normal and thus reduce distortion.

IMPEDANCE MATCHING

In all vacuum tube power work the necessity for impedance matching is encountered. At radio frequencies impedance matching usually can be accomplished by changing taps on a coil, varying the coupling, adjusting a variable condenser, or in some other relatively simple manner. At audio frequencies this is not so easy to do. Here large values of fixed capacity and iron core transformers are used. It is evident that the impedance matching requirements must be calculated before construction and the apparatus designed accordingly. Impedance matching is usually accomplished by means of a transformer. Just what is meant by "impedance matching"?

As an example, assume that it is desired to couple a single Type 2A3 power amplifier triode to a dynamic reproducer. The plate resistance of the tube is 800 ohms; assume that the reproducer has an impedance of 16 ohms. The turns ratio of the transformer to match these impedances can be calculated from the equation.

$$\text{Turns Ratio (Step Down)} = \frac{N_p}{N_s} = \sqrt{Z_p/Z_s}$$

where Z_p is the impedance across the primary and Z_s is the impedance across the secondary. With the values assumed above,

$$\text{Turns Ratio} = \sqrt{800/16} = \sqrt{50} = 7.07$$

Since to obtain the maximum undistorted output the tube must operate into a load impedance equal to two or more times the internal tube impedance, the turns ratio should be such that it will reflect a load from the secondary of the desired value.

$$2R_p = 1{,}600 \text{ ohms}$$

$$\frac{N_p}{N_s} = \text{Turns Ratio} = \sqrt{\frac{1600}{16}} = \frac{10}{1}$$

(Actually a higher load impedance is recommended for this tube, the manufacturer recommending 2,500 ohms.)

Now assume that this same reproducer is to be operated from two Type 2A3 tubes in push-pull, the tube manual recommended load is 5,000 ohms plate-to-plate for cathode bias at 300 volts on the plate. In this case

$$\text{Turns Ratio} = \sqrt{\frac{5000}{16}} = 17.7 \text{ to } 1$$

In the case of the output transformer of a push-pull Class B amplifier *where only one-half of the primary and one tube is operating at a time*, the primary must be considered as two separate primaries alternately coupled to the common secondary.

Assume that in such a circuit the tube manual recommends a load of 3,000 ohms plate-to-plate, then each tube should see a load of 750 ohms, and this value is to be reflected from a 10-ohm reproducer or loudspeaker.

The turns ratio between *one-half* the primary and the entire secondary will be,

$$\text{Turns Ratio} = .5N_p/N_s = \sqrt{750/10}$$

$$= \sqrt{75} = 8.66$$

The primary will then be made up of two windings in series, *each winding* having a turns ratio of 8.66 with respect to the common secondary, an overall step-down ratio of 17.32 to 1.

Impedance matching transformers are very often designed with taps so that a standard telephone line, for instance, may be coupled to any one of several circuits of different impedances. For example, the primary may be designed to offer an impedance of 500 ohms for connection to a 500-ohm telephone line with the secondary tapped for 10, 50, 100, 200, 300 ohms. Or any other combination can be arranged. It is only necessary that the turns ratio for each tap fulfill the requirement that,

$$N_p/N_s = \sqrt{Z_p/Z_s}$$

Where attenuation pads are used between two circuits of different impedance to provide a desired decrease in signal amplitude, it is always more desirable to use an impedance matching transformer than to design the attenuation pad for operation between unlike impedances.

TONE CONTROL

By "tone control" is ordinarily meant that the listener can, at will, vary the proportion of high and low audio frequencies that the receiver is capable of reproducing.

Tone control as usually employed does not build up the lower frequencies, rather, it attenuates the higher frequencies, thus making the lower frequencies sound louder in proportion to the higher frequencies. A very simple arrangement to accomplish this is shown in Fig. 10 (A), and in Fig. 10 (B) for a push-pull circuit. The principle is the same in both cases. With the minimum value of R, con-

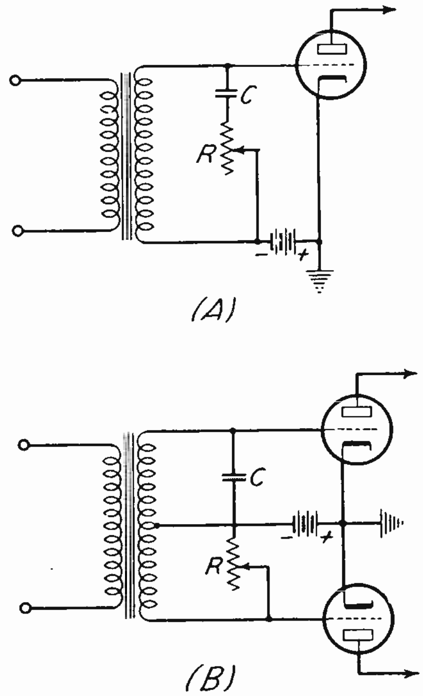

Fig. 10.--Tone control circuits.

denser C is directly across the tube input and the input transformer.

The higher the frequency the lower X_c, therefore with the minimum value of R, the higher frequencies will be short-circuited by C, and the higher the frequency the greater the signal loss through C. As the resistance of R is increased, the total impedance, $Z = \sqrt{R^2 + X_c^2}$, increases and less high-frequency signal is lost, until with a very high resistance at R the high frequency loss is negligible and, if the amplifier and reproducer are well designed, the tone is "natural". The high frequency cut off in such a circuit depends upon the capacity of C, the greater the capacity the lower the frequencies at which noticeable attenuation will result. With most receiver power amplifier triodes, C is usually between .01 µf and .03 µf while R may be from 50,000 ohms to as high as 1 megohm. An investigation of a number of standard receivers indicates that the most commonly used value of R is 50,000 ohms.

Lower values of C are used with the power pentode because of its higher input impedance, C usually being from .004 µf to .006 µf with R from 30,000 ohms to 100,000 ohms.

A problem somewhat similar to that of tone control is that of "tone compensation" to make up for too great selectivity in the i.f. amplifier. If the i.f. selectivity is too great, the higher frequency side bands will be greatly attenuated. In order to restore the higher frequencies to their normal proportion, the audio amplifier is so designed as to over-accentuate the higher frequencies in the proportion in which the r.f. amplifier attenuated those frequencies. How drastic this over-accentuation of the higher frequencies must be depends upon the selectivity of the i.f. amplifier, the greater the i.f. selectivity the more the higher frequencies must be amplified in the audio amplifier. One method of accomplishing this is by means of a high-pass filter connected between the detector and first audio stage. This is shown in Fig. 11. The higher the frequency, the easier it is passed through C, and the lower the frequency the easier it is by-passed through L, therefore the values of L and C can be designed to give any desired high-pass characteristics.

Of course, since both "frequency compensation" and "tone control" depend, for their operation, on the attenuation of certain frequencies in order to make other frequencies predominate, they require greater over-all gain in the amplifier to provide the same output in watts from a given input signal that would be obtained if such devices were not used.

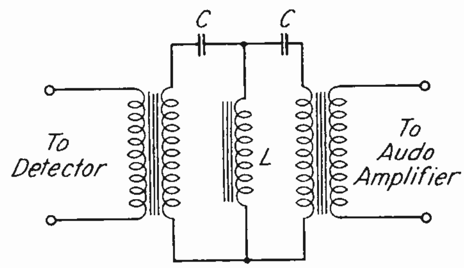

Fig. 11.--Tone compensation circuit.

BASS CONTROL AND AUTOMATIC BASS CONTROL (ABC)

In the design of an audio frequency amplifier for high fidelity broadcast reproduction, it is necessary that all frequencies between about 30 and 7,500 cycles (or higher) be reproduced in their proper proportion. In audio frequency reproduction other than in broadcast reception, it is desirable to extend the high frequency limit to 10,000 cycles or higher. For public address or theatre amplifiers where the output level is normally high, it is desirable that the amplifier response be "flat" over the entire frequency band.

However, in the broadcast receiver the output level is ordinarily not high, the level usually being reduced to comfortable small room volume. Under such conditions even if the audio amplifier response is flat down to quite low frequencies, the music tends to sound "tinny" at low volume. This is because the human ear is quite insensitive to low frequencies at a low power level. Thus, it is desirable, as the volume is decreased, to be able to accentuate the lower frequencies while still retaining full reproduction of the high frequencies—quite different from the operation of the so-called "tone control" which simply attenuates the higher frequencies. Such accentuation may be manual or automatic and is called respectively Bass Control or Automatic Bass Control. Any one of several systems may be used, the principle of all however being based on separate and additional amplification of the lower frequencies, ordinarily those below about 100 cycles, and the introduction of the additional low frequency component into the input of the main audio amplifier. One system of ABC as designed by the Hazeltine Corporation is shown in Fig. 12.

The operation of this circuit is quite simple. Neglecting temporarily the ABC part of the circuit, the signal at intermediate frequency is applied to the paralled diode units of the Type 55 tube, this forming the second detector, the rectified audio frequency current flowing through R_1, the potentiometer arrangement of this resistor forming the volume control. By means of potentiometer R_1 the desired audio voltage is applied to the grid of the triode section of the 55, this forming the first stage of a.f. amplification. The output of the first audio stage is transferred through C_5 and T_1 to excite the second audio amplifier consisting of two 56's in push-pull, this stage in turn exciting the final power amplifier consisting of two 2A3's in push-pull. Thus far, this is a conventional high-quality audio amplifier.

Assume that the volume control R_1 is adjusted so that the output to the reproducer is large. A portion of the output of the power amplifier is applied, through C_4, to the diode units of a second 55, the ABC tube. The capacity of C_4 is important. If C_4 is too small the voltage at the ABC diodes will be insufficient. If the capacity is too large the bass notes which it is desired to accentuate will over-excite the diode rectifier thus tending to decrease the bass. With the tubes shown, C_4 is .005 µf.

The rectified current flows through R_6 making point x negative with respect to ground. Point x connects through R_4 and R_3 to the control grid of the 57 audio amplifier, this grid also connecting through C_3 to the output of the second detector through the volume control R_1. With a large output from the power amplifier the voltage developed across R_6 is sufficient to block the 57. However, when the output decreases, due to an adjustment of R_1 or to very low passages in the musical program, the voltage across R_6 is decreased, the 57 tube is unblocked and begins to amplify the input from R_1.

The plate load circuit of the 57 consists of the parallel circuit L_1C_1 which is resonant to 75 cycles. This circuit offers inductive reactance to all frequencies below 75 cycles and tends to by-pass all higher frequencies through C_1. Thus, the low frequencies are amplified to a much greater degree than are the high frequencies, the quite high frequencies being almost entirely by-passed. The low frequency output is delivered to R_5 and by means of the variable contact the desired amplitude of low frequency voltage is used to excite the grid of the triode of the ABC 55 tube.

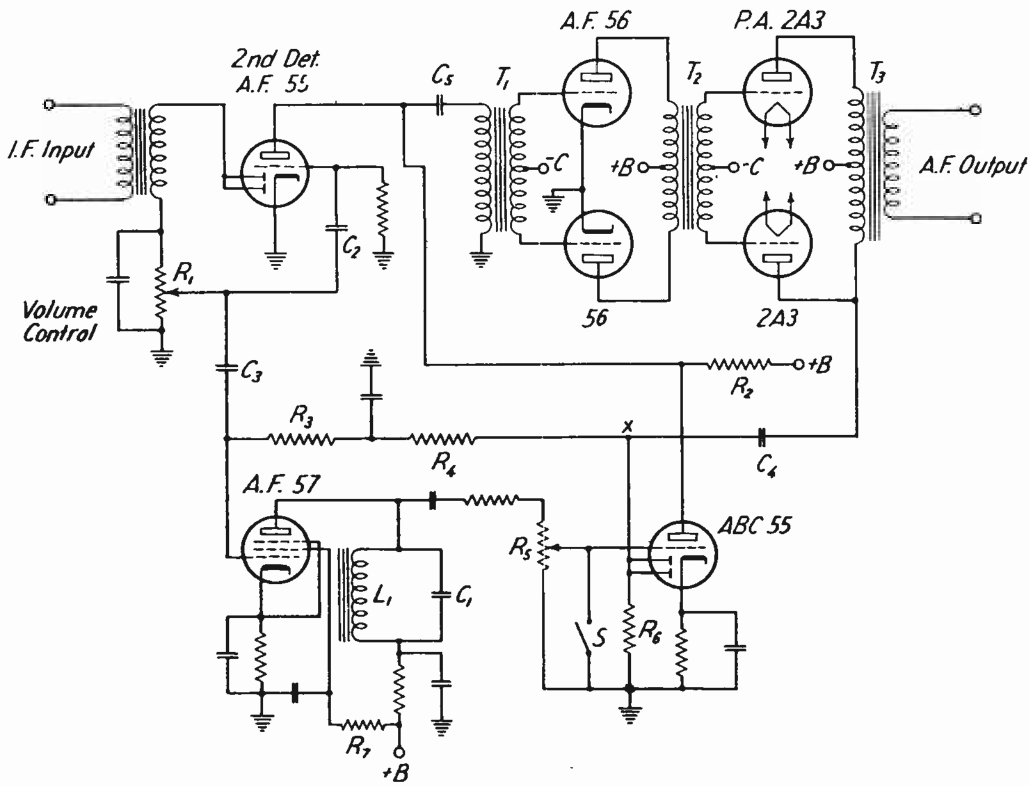

Fig. 12.--Automatic bass control circuit.

The output of the ABC 55 triode is connected to the output of the 55 triode section which serves as the first a.f. amplifier. Thus, by manipulation of the potentiometer R_5, called the Bass Control, any desired amount of bass accentuation can be obtained by adding a bass component into the input of the regular a.f. amplifier, without any attentuation of the higher frequencies. This allows the bass to be built up to a pleasing degree to make up for the natural deficiency of the ear when the volume is reduced to comfortable small room level. Switch S may be closed when it is desired to cut out the bass control without disturbing a predetermined setting of R_5.

Other bass control systems operate in a quite similar manner. One system by means of a three point potentiometer connection and a continuous resistor unit which allows the sliding contact to be continuously rotated, combines the features of the circuits of Figs. 10 and 12. On one half of the potentiometer the circuit is such that bass accentuation without high frequency attenuation is obtained in a manner similar to Fig. 12 but without the automatic feature. On the other half of the potentiometer the bass is not accentuated but the high frequencies are attenuated as in Fig. 10. This latter adjustment, while it destroys the fidelity of reproduction, is often very helpful in listening to a program through heavy atmospheric disturbances, most of the frequencies of which are quite high. Thus, fairly acceptable reception of a very long distance program is often possible where it would otherwise be entirely unfit to listen to due to excessive noise. Many tone control and bass control circuits are used but the principle of operation should not be hard for the student to analyze.

TYPES OF AUDIO AMPLIFIERS

In other assignments mathematical discussions of amplifier design, gain and frequency response are taken up. A brief tabulation of the conclusions will be given here.

RESISTANCE COUPLED AMPLIFIER.—The characteristics of this amplifier include moderate gain and a wide frequency response if properly designed. The gain can never exceed the amplification factor of the tube and in practice is usually between .5 μ and .75 μ. The greatest gain is at some intermediate frequency; the gain can be increased by increasing R_L, but the increase is slight after $R_L = 3R_p$. R_L is rarely made more than 2 or 3 times R_p. The low frequency gain is limited by the reactance of the coupling condenser. The high frequency gain is limited by the shunting input capacity of the next tube and the associated circuit capacities.

IMPEDANCE COUPLED AMPLIFIER.—The maximum gain is always less than μ but approaches μ more closely than in the case of the resistance coupled amplifier. The low frequency gain is limited by the low inductive reactance of the load impedance at low frequencies. The high frequency gain is limited, as in the resistance coupled amplifier, by the shunting capacities of the following tube and circuit. The frequency response curve is much less flat than that of the resistance coupled amplifier.

TRANSFORMER COUPLED AMPLIFIER.—The intermediate frequency gain over most of the frequency band will approximate μN, where N is the transformer turns ratio. This is true only if the amplifier and its component parts are well designed. The gain of such an amplifier can be made quite uniform over a considerable range of frequencies. Due to resonance the gain can, at certain fairly high frequencies, exceed μN. Beyond that point the gain curve usually cuts off quite sharply. The low frequency gain is limited by the low inductive reactance of the transformer primary at such frequencies. The high frequency gain is limited by the transformer leakage reactance and the shunting capacities. The use of permalloy for the transformer core instead of iron permits the obtaining of large inductance with the minimum number of turns and hence the minimum capacity, thus allowing the high frequency gain to be considerably extended.

The actual audio frequency response of a well designed amplifier is better than the voltage gain curve would seem to indicate. The ear, being logarithmic in response, is not so sensitive to even fairly large changes in voltage level, so that a gain curve plotted in decibels is a true response curve in terms of the ear. Such a curve is much more flat than is a voltage gain curve. By proper design of a two stage amplifier, one stage being peaked beyond the high frequency at which the gain of the other stage begins to fall off, a very flat overall response curve can be obtained. Due to the higher gain per stage and the simple circuit arrangement, transformer coupling is extensively used. The voltage and decibel gain curves of a stage of transformer coupled amplification are shown in Fig. 13. While between 50 and 6,500 cycles the *voltage gain* varies over a range of from 15 to 38, the total *variation*

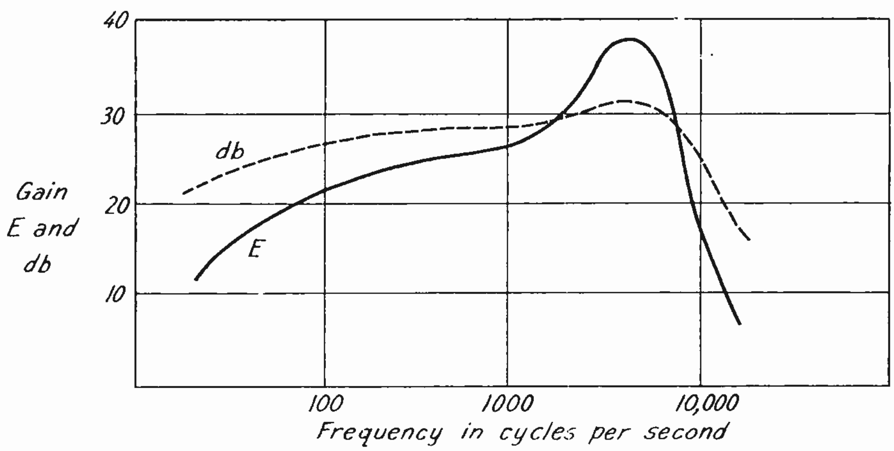

Fig. 13.--Amplifier gain curves.

in decibels over this frequency range is slightly more than 4 db, or about 2 db from the mean gain. Since this is just about the minimum that the average ear can detect, while the voltage gain curve looks very poor, to the ear the amplifier response is almost "flat" over the full range of reproduction. The peak at about 6,500 cycles is due to resonance caused by the transformer secondary inductance and stray capacities.

APPENDIX I

CORRECTION FACTOR FOR DIFFERENCE IN IMPEDANCE

It is to be noted that in audio circuits which operate over an extremely wide band of frequencies, the ordinary a-c wattmeter is inaccurate, especially at the higher audio frequencies, so that one is forced to use a voltmeter to indirectly measure the power in accordance with Eqs. (1) and (2).

In the case of gain measurements, the individual input and output powers are not required, but merely their ratio, so that if voltage measurements can be made, and *their* ratio noted, one can then tell what the power ratio is provided further that the impedance ratio is also known, as is indicated in Eq. (4) below as well as in the preceding text.

Thus, let

e_1 = input voltage across

R_1 = input resistance of amplifier or other four-terminal network;

e_2 = output voltage across

R_2 = output load resistance.

Then the power into the amplifier is

$$P_1 = e_1^2/R. \qquad (1)$$

And the output power is

$$P_2 = e_2^2/R_2 \qquad (2)$$

The db gain (or loss) is

$$A = 10 \log P_2/P_1 = 10 \log \frac{e_2^2/R_2}{e_1^2/R_1}$$

$$= 10 \log \left[(e_2^2/e_1^2)\ (R_1/R_2)\right]$$

$$= 10 \log (e_2/e_1)^2 + 10 \log (R_1/R_2) \qquad (3)$$

Since the logarithm of a product is equal to the sum of the logarithms of the individual factors, Eq. (3) can further be written as

$$A = 20 \log (e_2/e_1) + 10 \log (R_1/R_2) \qquad (4)$$

since the logarithm of the square is twice the logarithm of the number, itself. In Eq. (4), the first term 20 log (e_2/e_1) represents the logarithm of the voltage ratio multiplied by 20, whereas the logarithm of the power ratio is multiplied by 10. The second term 10 log (R_1/R_2) represents the *correction factor*, and is due to the fact that the output and input impedances R_2 and R_1 are in general unequal.

If, however, $R_1 = R_2$, $R_1/R_2 = 1$ and log (R_1/R_2) = log (1) = 0, and the correction factor drops out. In the general case of $R_1 = R_2$ the logarithm of the number is not zero and when the correction factor is added to the first term, gives the db gain when the measuring instrument is a voltmeter and reads voltage, instead of being a wattmeter and reading power.