is employed, however, or if some of the higher order side-band components are suppressed, the received signal will no longer be a true reproduction of the original audio signal.

When frequency modulation occurs with amplitude modulation the situation is somewhat less unfavorable than when phase modulation is present. This results from the fact that the modulation index m_f is inversely proportional to the audio frequency, so that at the higher audio frequencies the side-band components produced as a result of frequency modulation have relatively small amplitude. At low signal frequencies, where the modulation index m_f is large, the signal frequency is so low that the second- and third-order side bands lie well within the response band of the receiver and so are not suppressed by the receiver and do not produce interference with adjacent channels.

When phase, amplitude, and frequency modulation are combined the result at high audio frequencies is substantially that of phase and amplitude modulation alone, since the modulation index of frequency modulation is then small. On the other hand at the lower audio frequencies the combined result is very much the same as though there was only amplitude and frequency modulation, since here the modulation index m_f becomes so large as to make the phase-modulation index negligible by comparison.

CHAPTER XI

SOURCES OF POWER FOR OPERATING VACUUM TUBES

90. Cathode Heating Power.—The cathodes of vacuum tubes are heated with commercial alternating-current power whenever possible because of the convenience and low cost of such electrical energy. Alternating current cannot always be employed with filament-type tubes, however, and in some applications it is necessary to operate the filament on direct current or to use heater-type tubes.

Direct-current power for filament heating is usually obtained from either storage or dry batteries. Storage batteries are more economical and so are used whenever possible, while dry batteries find their chief usefulness in portable equipment and where power for recharging storage batteries is not available. Direct-current generators, and direct-current obtained by rectifying and filtering alternating current, are also occasionally used to heat the filaments of vacuum tubes.

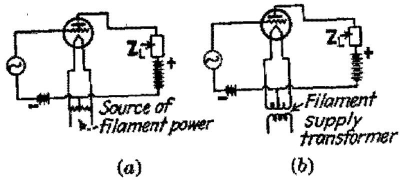

Fig. 200.—Methods of connecting the grid and plate return leads when alternating filament current is used.

When alternating current is supplied to the filament of a vacuum-tube amplifier which has been arranged for operation with direct-current filament power, the effect is to introduce into the amplifier output alternating currents of the frequency of the filament current and of twice this frequency. Furthermore any signal voltage that is being amplified by the tube will also be modulated slightly in accordance with the same two frequencies. The sum total of these effects is referred to as "alternating-current hum" since in radio sets and similar equipment the result is a low-pitched hum in the loud-speaker.

The part of the alternating-current hum that has the same frequency as the filament supply current can be entirely eliminated by bringing the grid and plate return leads to a point having the same potential as the mid-point of the filament. This is accomplished either by connecting the returns to the mid-point of a resistance located across the filament, as shown in Fig. 200*a*, or to a center tap on the filament transformer, as shown in Fig. 200*b*. Alternating-current operation of filaments in this way always calls for a slightly greater grid bias than is required for corresponding direct-current operation because the grid return lead is brought to a point that is positive with respect to the negative end of the filament.

Causes of Residual Alternating-current Hum from Alternating-current Filament Current.—After the fundamental frequency component of the alternating-current hum has been eliminated by one of the arrangements shown in Fig. 200, there remains a residual hum that has a frequency twice that of the filament current. This double frequency hum can arise from the cyclical variation of filament temperature, the effect which the alternating magnetic flux, set up by the filament current, has on the space current of the tube, and the effect which the voltage drop in the filament has on the space current. Since the heat generated in the filament at any instant is proportional to the square of the instantaneous filament current, the filament temperature will pulsate at twice the frequency of the filament current. The heat capacity of filaments used in vacuum tubes is so high, however, that the resulting variation in filament temperature is very small with 60-cycle filament current and produces negligible hum when temperature saturation is present.[1] The magnetic field produced by the filament current deflects the electrons flowing to the anode according to the principles discussed in Sec. 24 and causes the plate current to be slightly larger when the filament current is zero than when the current is at either a positive or a negative maximum. The voltage drop in the filament causes the negative half of the filament to supply more electrons to the anode than does the positive half, and since the number of electrons drawn from the filament is proportional to the three-halves power of the electrostatic field, the current from the negative end of the filament is increased more by the filament drop than the current drawn from the positive end is decreased. The total space current of the tube is hence slightly greater when there is a voltage drop in the filament than when the entire filament is at the same potential.

An exact analysis of the effect of the voltage drop in the filament shows that the resulting hum acts exactly as though it were produced by an alternating voltage applied to the grid of the tube, and that this equivalent alternating voltage that can be considered as being applied to the grid is directly proportional to the square of the alternating filament voltage and inversely proportional to the effective anode voltage $\left(E_g + \frac{E_p}{\mu}\right)$, where the grid and plate voltages E_g and E_p are measured with respect to the center point of the filament. If the hum voltage is to be kept low it is therefore apparent that a low-voltage filament is essential and that the effective anode voltage $\left(E_g + \frac{E_p}{\mu}\right)$ should be high,

[1] A detailed analysis of the factors producing the double frequency hum is given by W. J. Kimmel, The Cause and Prevention of Hum in Receiving Tubes Employing Alternating Current Direct on the Filament, *Proc. I.R.E.*, vol. 16, p. 1089, August, 1928.

i.e., that the plate current should be relatively large. The hum voltage produced by the voltage drop in the filament can be reduced to a considerable extent by using an inverted V-type of filament. This construction places the opposite ends of the filament in close proximity, causing the positive end to attract electrons from the negative leg with the result that the total space current is not increased as much by the voltage drop in the filament as would be the case if all of the electrons emitted from the filament went to the anode.

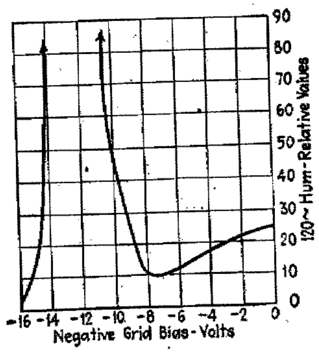

FIG. 201.—Variation of hum with grid bias in tube designed for alternating-current filament heating. At the proper grid bias the effects of the voltage drop in the filament and the magnetic flux of the filament current cancel each other, and the residual hum is very small.

The effects produced by the filament's magnetic field and by the voltage drop of the filament are of opposite phase, since the magnetic flux produced by a large filament current tends to reduce the anode current, while the voltage drop in the filament that accompanies this large current tends to produce an increased anode current. It is possible to take advantage of this cancelling effect to give a very low residual hum by using a low-voltage inverted V filament and giving the open end of the V the proper spacing to make the hum produced by the voltage drop in the filament balance out the hum resulting from the magnetic effect. The extent to which the hum can be reduced in this way is illustrated in Fig. 201 which shows that the balance between the two factors depends on the grid and plate potentials and can be made very good if the operating conditions are properly chosen.

Use of Alternating-current Power under Practical Conditions.—The use of alternating-current filament power is most successful in oscillators, power amplifiers, and radio-frequency amplifiers. Alternating filament current has negligible effect on the output of an oscillator and increases the filament life by distributing the direct-current plate current between the two sides of the filament better than when direct-current filament current is used. Power amplifiers operate satisfactorily with alternating-current filament current because the high effective anode voltage of such tubes makes the hum voltage relatively small provided a low-voltage filament is employed, and because the signal voltage applied to the grid of a power tube is always relatively large and so tends to drown out the small hum that may be present. Alternating-current power is also satisfactory for heating the filaments of radio-frequency amplifiers because the only effect of the hum voltage in such cases is to modulate the radio-frequency voltage by the van der Bijl method, and as the hum voltage is small the degree of hum modulation is almost insignificant.