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MODULATOR DESIGN MADE FLEXIBLE BY APPLICATION OF BASIC FORMULAS

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In most amateur applications the problem of choosing a suitable audio modulator circuit is affected at the start by certain fixed conditions in the ham shack. Usually, for example, the modulator plate-supply voltage is fixed by the power supplies available. Often the modulation transformer available has an "impedance" rating that may not fit the value of plate-to-plate load resistance published under the typical operating conditions for the modulator tubes desired. It is the purpose of this article to present simplified design formulas which will aid in the design of a satisfactory modulator stage.

Because efficiency and economy of operation are usually of the utmost importance, this discussion will be limited to push-pull circuits using (1) beam power tubes, (2) power pentodes, or (3) power triodes operating in the positive grid region. Screen-grid type tubes may be operated under either high-bias class AB_1 or class AB_2 conditions; triode types operate, of course, under high-bias class AB_2 or class "B" conditions.

Let us start off with values of dc plate voltage (E_{bs}) and dc plate current (I_{bs}) of the fully loaded class "C" rf stage which is to be plate modulated. These values have been either computed[1] or obtained from published class C telephony operating conditions for the desired tube type.

The average audio power (W_a) in watts required to fully modulate this input power with sine-wave modulation is obtained as follows[2]:

$$\text{Required average audio power } W_a = \frac{\text{dc plate voltage } E_{bs} \times \text{dc plate current } I_{bs}}{1.7} \qquad (1)$$

where E_{bs} is in volts and I_{bs} is in amperes.

The ac load resistance (R_s) in ohms presented to the modulation transformer secondary by the rf stage is given by

$$\text{AC load resistance } R_s = \frac{0.85\ E_{bs}}{I_{bs}} \qquad (2)$$

Equations (1) and (2) allow for an efficiency factor chargeable to the modulation transformer and arbitrarily set at 85%. No specific allowance has been made for

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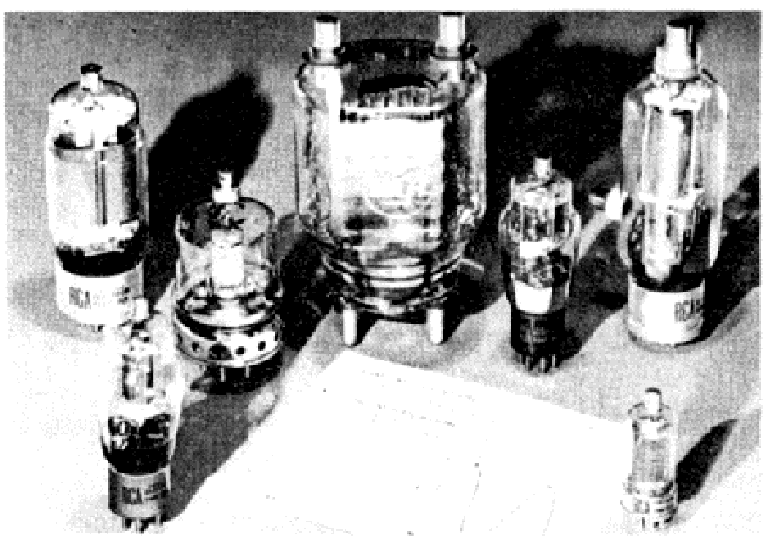

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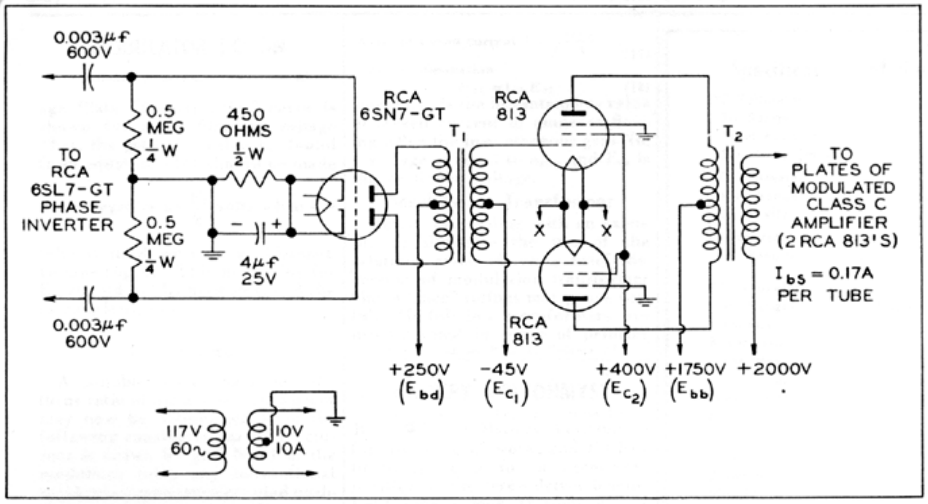

Figure 1. Modulator circuit designed from calculations given in text. It has not been built, and therefore, test data are not available.

Notes:
1) All power supplies returned to ground.
2) E_{c1} to be obtained from a source of good regulation (internal impedance equal to or less than 200 ohms).
3) The 250-volt supply may be obtained from a tap on bleeder for E_{c2} supply. Minimum bleeder current should be approximately 0.05 amperes.
4) T_1 = Driver Transformer—5-watt audio level—Total primary to ½ secondary turns ratio = 3.
5) T_2 = Modulation Transformer—400-watt audio level—one-half primary to total secondary turns ratio = 0.8.
6) E_{c2} and E_{bb} supplies should be adequately bypassed to ground for audio frequencies. Radio-frequency bypass capacitors at tube socket may be required under some conditions.

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screen-modulation power which is usually negligible if a screen-voltage tap is available on the modulation transformer. If a dropping resistor is used to supply the screen with modulated voltage, the screen current per tube of the modulated stage should be added to I_{bs} before W_s and R_s are computed. It should be noted that satisfactory plate modulation of screen-grid tubes often results if the screen is fed from an unmodulated voltage source through an audio choke or a high resistance.

Design Procedure

Let us assume that the dc plate supply voltage for the modulator stage (E_{bb}) is fixed, and the design problem is to select suitable modulator tubes and a modulation transformer to meet the conditions imposed above. The following approximate relations will be used:

For E_{bb} in range from 400 to 750 volts	For E_{bb} in range from 1250 to 3500 volts	
$I_b = \frac{0.75\ W_a}{E_{bb}}$	$I_b = \frac{0.71\ W_a}{E_{bb}}$	(3)
$W_p = 0.25\ W_a$	$W_p = 0.21\ W_a$	(4)
$W_{in} = 0.75\ W_a$	$W_{in} = 0.71\ W_a$	(5)
$R_{pp} = \frac{1.3\ E_{bb}^2}{W_a}$	$R_{pp} = \frac{1.7\ E_{bb}^2}{W_a}$	(6)

$$r = \sqrt{\frac{R_{pp}}{4R_s}} \quad (7)$$

In the above relations, I_b is the max.-signal dc plate current *per tube* in amperes, W_p is the max.-signal plate dissipation *per tube* in watts, W_{in} is the max.-signal dc power input per tube in watts, and W_a is the audio power output for *two tubes* (push-pull stage) also in watts, all for sine-wave modulation. R_{pp} is the plate-to-plate load resistance presented to the modulator tubes, and r is the turns ratio of the modulation transformer defined as

$$\text{Modulation transformer turns ratio } r = \frac{\text{½ total number of primary turns}}{\text{number of secondary turns}} \quad (8)$$

It is assumed, of course, that the primary of the modulation transformer is center tapped and that the secondary feeds the class "C" rf stage to be plate modulated.

Modulator Tube Selection

Suitable modulator tubes (either screen-grid or triode types) may now be selected on the basis of maximum ratings[3] for either class AB_2 or class B audio service (or class C telegraphy ratings if audio ratings are not given) that are equal to or in excess of the values found from equations (3) to (6). It is evident from inspection of equations (6) and (7) that the selection of E_{bb}, R_s, and W_a automatically fixes the modulation transformer turns ratio, r. If a transformer having a different turns ratio is already available in the ham shack it will be necessary to change either one or all of the three quantities listed in order to make use of this transformer. If the turns ratio of the available modulation transformer is lower than the value given by equation (7), it is possible to operate the modulator tubes into a lower than optimum value of R_{pp}. However, unless E_{bb} is lowered also, this mode of operation is very inefficient and equations (3), (4), (5), and (6) are no longer valid. It should be noted that

$$\text{Modulation transformer turns ratio } r = \sqrt{\frac{Z_p}{4Z_s}} \quad (7a)$$

where Z_p is the rated "impedance" of the total primary winding and Z_s is the rated "impedance" of the secondary winding.

After a suitable tube type has been selected, the published "Average Plate Characteristics" curves ("plate family") for this type should be used to determine suitable operating values. For screen-grid tubes a value of screen-grid voltage—and suppressor-grid voltage, if required—which can be readily obtained in the ham shack from a power source having good voltage regulation must be selected. A straight (load) line is drawn on the "plate family" curves connecting the point determined by "Plate Amperes" = 0 and "Plate Volts" = E_{bb} to the point determined by "Plate Volts" = 0 and "Plate Amperes" = I'_b where

$$I'_b = \frac{4E_{bb}}{R_{pp}} \quad (9)$$

The optimum value of grid-No. 1 bias may now be obtained from the relation

$$\text{Optimum grid bias } E_{c1} = -\frac{(e_1 i_2 - e_2 i_1)}{(i_1 - i_2)}, \quad (10)$$

where the values of e_1 and e_2 are convenient intermediate values of grid-No. 1 voltage taken from the intersection of the load line with the bias curves, and i_1 and i_2 are the corresponding plate currents. In this equation it is assumed that the "e" and "i" points chosen lie on a linear portion of the tube's dynamic transfer characteristic and that the plate current of the non-working tube of the push-pull connection is zero. For this reason, the values of "e" and "i" chosen for equation (10) should lie well up on the load line but should not include points near the "knee" of the curve where some non-linearity may usually be expected. The plate dissipation under zero-signal conditions (W_{po}) may now be checked. Proceeding vertically upwards from E_{bb} on the "plate family" curves, read the value of plate current I_{bo} at the value of E_{c1} computed from equation (10). Then,

$$\text{Zero-signal plate dissipation } W_{po} = E_{bb} I_{bo} \quad (11)$$

This value of W_{po} (zero-signal plate dissipation per tube) should not exceed approximately 1/3 to 1/2 of the maximum rated plate dissipation of the tube. If the value of E_{c1} found from equation (10) is not sufficiently negative to limit W_{po} to the desired value, it may be made more negative at the expense of only a slight increase in distortion at max.-signal levels; small-signal operation will produce larger amounts of distortion, but this mode of operation is generally of no consequence in modulator designs for voice communication. The peak af grid-No. 1-to-grid-No. 1 voltage (E_{gg}) in volts may be obtained from

$$\text{Peak af grid-No. 1-to-grid-No. 1 voltage } E_{gg} = 2\,(e_{gm} - E_{c1}) \quad (12)$$

where e_{gm} is the instantaneous grid voltage obtained from the "plate family" curves at the intersection of the load line with the knee of the curve. If the tube chosen is a filamentary type and if the "Aver-

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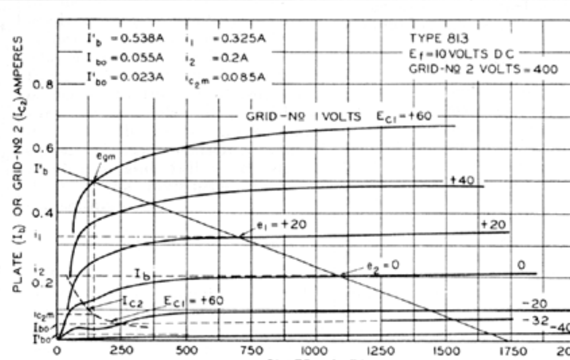

Figure 2. Average plate characteristics of the RCA-813.

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age Plate Characteristics" curve is shown for a dc filament voltage (E_f), the grid bias value E_{c1} found from equation (10) should be made more negative by $\frac{E_f}{2}$ volts when the tube is used with an ac filament-voltage supply. This new value for E_{c1} should not be used in any of the calculations, however.

Driver Stage

A suitable driver stage and the turns ratio of the driver transformer may now be determined from the following considerations. If no current is drawn by grid No. 1 of the modulator tube, any conventional resistance-capacitance-coupled push-pull or phase-inverter voltage amplifier, comprising either triodes or pentodes, capable of supplying the required value of peak af grid-No. 1-to-grid-No. 1 voltage E_{gg} to the modulator circuit may be used.[4] If current is drawn by grid-No. 1 of the modulator tube, the following approximate relations are useful. For conventional low- and medium-mu triodes for the driver stage in push-pull class A or AB_1 connection

The driver transformer turns ratio r_d =

$$\frac{2.4E_{bd}}{E_{gg}} \quad (13)$$

and

Driver tube max. allowable plate resistance

$$R_{pm} = \frac{r_d E_{bd}}{6.7\, i_{gm}} \quad (14)$$

where r_d is the driver transformer turns ratio and is defined as

$$r_d = \frac{\text{total number of primary turns}}{\frac{1}{2}\text{ number of secondary turns}} \quad (15)$$

E_{bd} is the plate supply voltage of the driver stage, i_{gm} is the instantaneous grid current drawn by grid No. 1 of the modulator tube in amperes at the value of e_{gm} used in equation (12), and R_{pm} is the maximum allowable driver-tube plate resistance in ohms. Tubes with values of R_p higher than indicated by equation (14) may be used but somewhat higher distortion will result. For single-ended class A driver circuits using conventional low- and medium-mu triodes

$$r_d = \frac{1.2\, E_{bd}}{E_{gg}} \quad (16)$$

Equations (14) and (15) also apply in this case. The power rating of the driver transformer should be adequate to handle at least the rated power output of the driver tube(s) in conventional class "A" (or AB_1 as the case may be), audio power-amplifier service.

The final value to be determined in computing tube operation is the screen-grid dissipation. Useful relations for approximating the value of average screen current (I_{c2}) in amperes and screen dissipation (W_{c2}) in watts at max.-signal levels are

Average screen current $I_{c2} = \frac{i_{c2m}}{4}$ (17)

Screen dissipation

$$W_{c2} = I_{c2}\, E_{c2} \quad (18)$$

where i_{c2m} is the instantaneous value of screen current in amperes flowing when the instantaneous grid-No. 1 voltage is equal to e_{gm}, and E_{c2} is the dc screen voltage.

Modulation Transformer

Before proceeding with an example to illustrate the use of the relations given above, a brief discussion of modulation transformer "impedance" ratings may prove useful. Modulation transformers are usually rated in terms of primary

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and secondary "impedance" and audio power (or more properly KVA) capability. The peak ac voltage (E_{pm}) that may be applied to ½ of the modulation transformer primary is

Peak ac voltage across primary $E_{pm} =$

$$\sqrt{\frac{W_t Z_{pm}}{2}} \qquad (19)$$

where Z_{pm} is the maximum impedance rating of the entire primary in ohms and W_t is the rated audio-power-handling capability of the transformer in watts. Similarly, the peak ac voltage (E_{sm}) permissible across the transformer secondary winding (equal to the dc plate voltage of the plate-modulated rf amplifier for 100% modulation) may be found from

Peak ac voltage across secondary $E_{sm} =$

$$\sqrt{2\, W_t Z_{sm}} \qquad (20)$$

where Z_{sm} is the maximum secondary-impedance rating of the transformer. Of course, any voltage (and impedance) lower than these maximum rated values may be used. However, in order not to exceed the ac current ratings implied in the audio power and impedance ratings of a transformer having a fixed turns ratio, the power-handling capability of a transformer should be reduced approximately in accordance with the relation

$$W'_t = \frac{W_t R_s}{Z_{sm}} \qquad (21)$$

where R_s (as defined previously for equation (2)) is *less* than Z_{sm} and W'_t is the reduced audio-power-handling capability of the transformer. The dc current ratings of both primary and secondary windings are assumed to remain constant when the transformer is operated at other than rated impedance levels, although a reduction in primary dc current may allow some increase in ac current (allowing W'_t as given in equation (21) to be increased somewhat) and a reduction in secondary dc current may allow a slight increase in both E_{sm} (as given in equation (20)) and W'_t. For modulation transformers of the "multimatch" type it is assumed (unless information to the contrary is published by the manufacturer) that full power-handling capability has been preserved by proper design for all rated impedance values.

Example

As an example, let us assume that the class "C" rf amplifier to be modulated is a push-pull circuit using 2 RCA-813's with a dc plate voltage (E_{bs}) of 2000 volts and a dc plate current (I_{bs}) of 0.17 amperes for each tube or 0.34 amperes for both. From equation (1), we obtain

Required average audio power $W_a = \frac{E_{bs} I_{bs}}{1.7} = \frac{(2000)\ 0.34}{1.7} = 400$ watts

From equation (2), we obtain

AC load resistance $R_s = \frac{0.85 E_{bs}}{I_{bs}} = \frac{0.85\ (2000)}{0.340} = 5000$ ohms

If we assume that it is desired to operate the modulator from a 1750-volt supply, equations (3) to (5) yield

Max.-signal dc plate current per tube $I_b = \frac{0.71 W_a}{E_{bb}} = \frac{0.71\ (400)}{1750} = 0.162$ amperes

Max.-signal plate dissipation per tube $W_p = 0.21 W_a = 0.21\ (400) = 82$ watts

Max.-signal dc power input per tube $W_{in} = 0.71 W_a = 0.71\ (400) = 284$ watts

Inspection of the maximum ratings in the technical data[5] for power tubes shows that either the RCA-813 or the RCA-810 types will easily fulfill all requirements. If a 400-volt screen supply having good regulation is available, the 813 may be chosen to advantage, because this choice will ease the driver stage requirements somewhat in comparison to those required for the RCA-810. Equations (6) and (7) give us the required modulation-transformer impedance and turns ratio ratings.

Plate-to-plate load resistance $R_{pp} = \frac{1.7 E_{bb}^2}{W_a} = \frac{1.7\ (1750)^2}{400} = 13{,}000$ ohms

Turns ratio of modulation transformer $r = \sqrt{\frac{R_{pp}}{4R_s}} = \sqrt{\frac{13{,}000}{4\ (5000)}} = 0.806$

The load line can now be drawn on the curve of "Average Plate Characteristics" shown in Fig. 2 after I'_b is obtained by means of equation (9) as follows

$I'_b = \frac{4E_{bb}}{R_{pp}} = \frac{4\ (1750)}{13{,}000} = 0.538$ amperes

From equation (10) after points e_1 and e_2 have been selected, we obtained

Optimum grid bias $E_{c1} = -\left(\frac{e_1 i_2 - e_2 i_1}{i_1 - i_2}\right)$

$= -\left(\frac{20\ (0.2) - 0\ (0.325)}{0.325 - 0.2}\right) = -\frac{4}{0.125} = -32$ volts

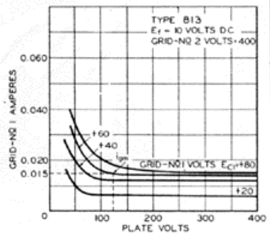

Figure 3. Grid characteristics of the RCA-813.

The value of I_{bo} at a grid bias of −32 volts is obtained from the family of average plate characteristics and then, from equation (11), we determine

Zero-signal plate dissipation $W_{po} = E_{bb} I_{bo} = (1750)\ (0.055) = 96$ watts

Because this dissipation value is in excess of ½ the maximum plate-dissipation rating; that is, greater than $\frac{125}{2}$ or 63 watts, a higher grid bias must be chosen. If a grid bias of −40 volts is used, the zero-signal plate dissipation is

$W_{po} = E_{bb} I_{bo} = (1750)\ (0.023) = 40$ watts

which is a satisfactory value.

From equation (12), we can determine

Peak af grid-No. 1-to-grid-No. 1 voltage $E_{gg} = 2\,[e_{gm} - E_{c1}] = 2\,[60 - (-40)] = 200$ volts

For ac filament operation, an actual bias of −45 volts is required because the average plate characteristics were taken with a dc filament power supply of 10 volts.

If we assume that a push-pull driver stage having a plate supply voltage (E_{bd}) of 250 volts would be most desirable, then from equation (13) we obtain

Driver transformer turns ratio $r_d = \frac{2.4\, E_{bd}}{E_{gg}} = \frac{2.4\ (250)}{200} = 3$

From Fig. 3, at the value of instantaneous grid-No. 1 voltage obtained from the plate family curves at the intersection of the load line with the knee of the curve, e_{gm} = 60 volts. At a plate voltage corresponding to the intersection of the load line and the curve of e_{gm} = 60, the value of instantaneous grid-No. 1 current (i_{gm}) is 0.015 amperes.

Hence, from equation (14) the maximum allowable plate resistance of the driver tube (R_{pm}) is given by

$R_{pm} = \frac{r_d E_{bd}}{6.7\, i_{gm}} = \frac{3\ (250)}{6.7\ (0.015)} = 7460$ ohms

An RCA 6SN7-GT in push-pull class "A" connection will meet the requirements for a driver tube. From Fig. 2 the instantaneous screen current (i_{c2m}) is found to be 0.085 amperes.

From equations (17) and (18), we obtain

Average screen current $I_{c2} = \frac{i_{c2m}}{4} = \frac{0.085}{4} = 0.021$ amperes

Screen dissipation $W_{c2} = E_{c2} I_{c2} = 400\ (0.021) = 8.5$ watts

This value is well within the ratings for screen power input for the RCA 813. All the pertinent design information for the modulator is given in Table I. Fig. 1. is a typical circuit based on these values.

TABLE I
AUDIO MODULATOR USING 2 RCA-813's IN CLASS AB_2

Values are for 2 tubes

DC Plate Voltage	1750 volts
DC Grid- No. 3 Voltage	0 volts
DC Grid- No. 2 Voltage	400 volts
DC Grid- No. 1 Voltage*	−45 volts
Peak AF Grid- No. 1 to Grid- No. 1 Voltage	200 volts
Zero-Signal DC Plate Current	0.046 amperes
Max.-Signal DC Plate Current	0.324 amperes
Max.-Signal DC Screen Current	0.042 amperes
Effective Load Resistance (Plate-to-plate)	13,000 ohms
Max.-Signal Power Output	400 watts
Output Transformer Turns Ratio, r	0.806
Driver Transformer Turns Ratio, r_d	3
Driver Tube	6SN7-GT (or equivalent)

* For AC filament operation

HAM TIPS is published by the RCA Tube Department, Harrison, N. J., and is made available to Amateurs and Radio Experimenters through RCA tube and parts distributors.

H. S. STAMM, W2WCT .... *Editor*

FOOTNOTES

1. "Simplifying the Calculation of Transmitting Triode Performance" by E. E. Spitzer, "Ham Tips". Nov.-Dec. 1948.
2. Although it is true that considerably less average audio power than the value of Wa given above is required for voice modulation, the peak power capability of the modulator must be adequate if severe distortion at the voice peaks is to be avoided. It is necessary, therefore, to compute the modulator circuit constants for sine-wave signal conditions. Somewhat lower values of plate dissipation than those calculated later will result if voice modulation is used exclusively and this fact may therefore be considered in selecting suitable modulator tubes on the basis of their maximum plate dissipation rating (and, incidentally, in choosing the dc current rating of the modulator plate supply). It is well to remember, however, that if the modulator tubes are chosen with a plate dissipation rating that is only "just sufficient" for voice modulation, a sustained whistle into the "mike" or several seconds of rf, audio circuit, or acoustical feedback, will produce excessive plate dissipation and may result in tube failure.
3. See footnote 2.
4. See pages 196ff in RCA Receiving Tube Manual, RC-15.
5. RCA Tube Handbook HB-3; Headliners for Hams, HAM-103.