The Grounded Grid Linear Amplifier

In the "good old days" of ham radio, linear amplifiers were used by a few amateur phone stations as a (relatively) inexpensive way of obtaining high power. Class B modulators were as yet unknown, and the cost of glassware necessary to generate two or three hundred watts of Class A audio power was exhorbitantly expensive for all but the "well-heeled" hams.

Loy Barton's classic QST article (Cira 1929) describing the inexpensive Class B modulator system sounded the death-knell of the linear amplifier for amateur service until the advent of single sideband, which recently blew the dust from this ancient mode of operation and modernized it to fit today's operating conditions.

What is a Linear Amplifier?

To the hi-fi enthusiast, the linear amplifier is a high fidelity music amplifier. To the SSB enthusiast, the linear amplifier package, when placed on the end of a sideband exciter, will make the exciter sound bigger, louder, and more commanding to other amateurs. The fact of the matter is that the SSB linear amplifier is a high fidelity amplifier in the true sense of the word. The "hi-fi" man thinks in terms of fidelity, and the "sidebander" thinks in terms of linearity. They are both talking the same language.

It is interesting to note that a good "hi-fi" audio amplifier can be theoretically converted to a low distortion linear amplifier for sideband service by replacing the audio circuits with suitable r.f. tank circuits. Indeed, for r.f. work, push-pull circuitry is not even required as it is in audio service, because the flywheel action of the r.f. tank circuits will supply the missing half-cycle. Finally, the operating parameters for a particular tube (plate, screen and grid voltage; driving voltage; and load resistance) are easily calculated for audio work, and apply equally well for r.f. service. For example, the 811A tube is rated for Class B audio service, as a high-μ triode (figure 1A). Compare these ratings with the Class B r.f. linear data listed in figure 1B.

Why Linearity?

For sideband service, the r.f. power amplifier must be truly linear. It must be capable of high fidelity reproduction, That is, the signal existing in the plate circuit must be an exact replica of the exciting signal impressed upon the input circuit. This statement is a good definition of a linear amplifier. It implies that the power gain of the stage must be constant regardless of the signal level. Any deviation from this happy state creates distortion products that appear in the signal passband and adjacent to it.

Unfortunately, many amateurs judge the excellence of the sideband signal by the quality of the signal; that is the pleasing aspect of the voice being transmitted. Many times one hears the report "Your quality is excellent, Old Man. You have a fine signal", yet the listener observes that the recipient of this flattering observation has a signal as broad as a barn door, complete with "whiskers" and "splatter" that obliterate half the phone band! Obviously, the criteria of quality of a sideband system is what you don't hear, not what you do! The place to examine a sideband signal for linearity and quality is in an adjacent channel, not in the frequency band of the signal itself!

How Good is "Good Quality"?

The excellence of a sideband signal is an ethereal concept and usually is judged by the amount of (or lack of) sideband splatter in nearby channels. Theoretically, a sideband signal should be about three or four kilocycles wide: just as wide as the voice passband of the equipment. However, the poor sideband operator's "tin ear" has been brutally deafened by so many "rotten signals" that he often accepts any SSB signal as "good quality" as long as it does not blanket the dial of his receiver!

Over the years a nice, easy, vague figure of "30 decibels down" for distortion products has become a password for good quality, low distortion, amateur sideband equipment. Since the measurement technique is usually undefined, and practically no amateurs have equipment sufficiently sophisticated to measure the intermodulation products of a sideband signal, this figure has become a byword for most commercial and home-made amateur equipment on the air. Valid or not, this magic number seems to be the socially correct distortion figure applicable in all cases to all equipment!

Distortion - What it Means

If the output signal of a linear amplifier stage is a replica of the exciting signal, there will be no distortion products. However, as vacuum tubes and circuit components are not perfect, this situation is as yet unreachable. As shown in figure 2, the transfer characteristic of a typical tube is approximately linear. This tube suffers no pain when amplifying a single signal (such as a carrier or a single tone), but has the interesting property of mixing when a multiple signal source is applied to it. This means that a voice signal (made up of a multiplicity of tones) will become distorted and blurred by the inherent mixing action of a so-called linear or "high fidelity" amplifier. A standard test to determine the degree of mixing for a given circuit or tube is the two-tone test, wherein two radio frequencies of equal amplitude are applied to the amplifier, and the output signal is examined for spurious products (figure 3). These products, or "garbage" fall in the fundamental signal region and atop the various harmonics. The tuned circuits of the amplifier filter out the spurious signals falling in the harmonic regions, which are termed even-order products. The odd-order products, unfortunately, fall close to the fundamental output frequency of the amplifier, and cannot be removed by simple tuned circuits. These are the spurious frequencies that cause a poorly designed or incorrectly adjusted linear amplifier to cover the dial with splatter. Shown in the illustration are two frequencies that make up a typical two-tone test signal. In this example, they are 2000 kc. and 2002 kc. Now, if the amplifier is perfect, these two signals will be the only ones appearing in the output circuit. An imperfect (but practical) amplifier, however, will have various combinations of sums and differences of the signals and their harmonics which are generated by the nonlinearity transfer characteristic of the tube. All of these unwanted products fall within the passband of the tuned circuits of the amplifier and are radiated, along with the two test tones.

If the odd-order products are sufficiently attenuated, they will be of minor importance and can be ignored. The sixty-four dollar question is: of what magnitude can these spurious products be without becoming annoying? How much "garbage" can be permitted before the signal becomes intolerable to the operator trying to maintain a QSO in an adjacent channel?

The answer to these questions depends upon the type of information being transmitted, and the degree of interference that can be tolerated in the adjacent channel. Certain forms of information (not voice) require an extremely low value of spurious products within and adjacent to the pass band; otherwise, the information will be seriously degraded. Odd-order products greater than .001% of the wanted signal may be damaging to the intelligence. Translated into terms of decibels, this means the unwanted odd-order products must be -50 decibels below the wanted signal! This takes some doing, and is orders of magnitude more strict than the level of intermodulation products than cat be tolerated in amateur voice communications.

In actual practice, it would seem that odd-order products less than 0.1% of the peak signal level are sufficiently attenuated so as to cause a tolerable level of adjacent channel QRM in everyday amateur communications. This indicates a distortion product magnitude of -30 decibels below the peak output power level of the transmitter. Such a state of affairs can be obtained by modern techniques without too much trouble provided attenuation is given to circuit design and operating parameters of the equipment. Of course, if distortion levels exceeding this arbitrary level can be reached, so much the better! Unfortunately, some equipments presently operating in the amateur bands and masquerading as "linear" amplifiers exhibit distortion levels of -20 decibels or less below peak power output! Use of equipment of this dubious quality quickly reduces the popularity of the operator to zero, and will probably lead to a brick through the shack window if continued!

The Grounded Grid Linear Amplifier

For amateur service the grounded grid circuit professes to be the answer to many of the ills besetting the linear amplifier. It requires a level of drive that is compatible with the great majority of sideband exciters (70 to 100 watts). With proper choice of tubes, it may be operated in a zero bias condition, eliminating the need of expensive and heavy grid (and screen) power supplies. Neutralization is not usually required. In addition, claims are made that the "inherent" feedback of the grounded grid amplifier improves the stage linearity and drops the magnitude of the distortion products. This all sounds too good to be true, and an examination of the grounded grid amplifier may be in order to see if it is "the answer to the sidebander's prayers".

The "classic" grounded grid amplifier is shown in figure 4A. The control grid is at r.f. ground potential, and the driving signal is applied to the cathode via a tuned circuit. The control grid serves as a shield between the cathode and the plate, making neutralization unnecessary at medium and high frequencies.

The input and output circuits of the grounded grid amplifier may be considered to be in series and a certain portion of the input power appears in the output circuit. This feedthrough power acts to somewhat stabilize the load the amplifier presents to the exciter, and also provides the user with some "free" output power he would not otherwise obtain from a more conventional circuit. The driver stage for the grounded grid amplifier must be capable of supplying the normal level of excitation power required by the amplifier plus the feedthrough power. Stage power gains of 5 to 25 can be achieved in a grounded grid amplifier.

Measurements made on various tubes in the Power Grid Tube Laboratory of EIMAC showed that an improvement of 5 to 10 decibels in odd-order distortion products may be gained by operating various tubes in the grounded grid configuration of figure 4A, in contrast to the same tubes operating in the grid driven mode. The improvement in distortion figure varied from tube type to tube type, but all tubes tested showed some order of improvement when cathode driven. (See Amateur Service Bulletin #1 for information regarding cathode driven service).

The tuned cathode circuit consisted of a bifilar coil which carried the filament current and a large capacity variable capacitor. The circuit was high-C, with the excitation tap placed to provide a low value of SWR on the coaxial cable to the exciter.

The Untuned Cathode Circuit

After sufficient measurements had been made with the circuit of figure 4A, the apparatus was modified to simulate the popular untuned cathode input circuit of figure 4B. It was immediately noted that the tubes tested in the previous circuit provided noticeably poorer results when used with an untuned cathode circuit. Power output dropped by 5% or so, greater grid driving power was required, and linearity suffered to a degree. Specifically, the third-order products rose approximately 3 to 4 decibels over the values produced by the circuit of figure 4A, and the fifth-order products rose 5 to 6 decibels over those figures recorded with the tuned cathode circuit. The higher order distortion products also rose accordingly. Observing the input waveform at the cathode of the grounded grid amplifier showed a pronounced distortion of the r.f. waveform caused by the loading effect over one-half cycle caused by a single-ended class B amplifier. Plate and grid currents drawn over the portion of the cycle loaded the input circuit. The exciter thus "sees" a very low load impedance over a portion of the cycle, and an extremely high impedance over the remaining part of the cycle. Unless the output regulation of the exciter is very good, the portion of the wave on the loaded part of the cycle will be seriously degraded, as shown in figure 5. Under normal circumstances, degradation of the input waveform may reach a more serious degree, as the exciter used for these tests was operating Class A and was well swamped to improve regulation. Obviously, the circuit Q of the exciter output tank at the end of a random length of interconnecting coaxial line is not sufficient to prevent this form of wave distortion. In addition to degrading the intermodulation figure, this waveform distortion also can cause mysterious TVI troubles as a result of the high harmonic content of the wave.

It was also noted that the degree of intermodulation distortion could be changed by varying the length of coaxial line between the driver and the linear amplifier! This pointed out a problem that had gone unnoticed until now (figure 6). When the untuned cathode circuit is used, the r.f. current path from the plate of the amplifier tube back to the cathode must follow the path of the dotted line in the drawing. Since the cathode choke offers a high impedance to this path, the alternative circuit is via the outer shield of the coaxial line, through the output capacitor of the exciter plate tank circuit, back to the linear amplifier via the center conductor of the coaxial line, and through the coupling capacitor to the cathode of the amplifier tube!

This alternative path presents several severe hazards. First of all, it is random, and varies with the length of interconnecting coaxial line. Second, the outer shield of the coaxial line is "hot" to the plate circuit ground return, and all sorts of weird intercoupling between the amplifier and the exciter may result. Third, the plate return current passes through the output pi-network capacitor of the exciter. There is a real danger that this capacitor may not be large enough (in a physical sense) to carry the current, and may be damaged when subjected to this form of abuse.

It is possible to employ either a high-C tuned circuit of the form shown in figure 7A, or untuned filament chokes in conjunction with a simple pi-network may be employed as shown in figure 7B. Either arrangement will supply the necessary "flywheel" effect to retain good r.f. waveform at the cathode of the linear stage, and both will provide a short, direct ground return path for the plate r.f. circuit.

Adjustment of the Cathode Circuit

The cathode circuit is resonated to the operating frequency by means of the variable capacitor. Resonance is indicated by maximum grid current of the amplifier. A low value of SWR on the coaxial line to the exciter is established by adjusting the tap on the tuned circuit, or by varying the "input" capacitor of the pi-network. SWR correction should be made with the amplifier running at maximum input. When the tap is correctly set, maximum grid current and minimum SWR will coincide at one setting of the capacitor. No cutting and trimming of the coaxial line is required, and the exciter will be properly loaded. This is a boon, indeed, to the owners of SSB exciters that have a fixed pi-network output circuit.

Summary

The use of the tuned cathode circuit in a grounded grid linear amplifier stage improves linearity, increases the power output, makes the stage easier to drive, and reduces the burden placed on the sideband exciter. The advantages of this circuit are well worth the added cost of parts and the extra controls. It is, of course, possible to dispense with the tuned cathode circuit, provided the user understands the handicaps he must assume by omission of this important circuit element.

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Figure 1

811A OPERATING DATA			
(A) Class B Audio Service (Two Tubes)		(B) Class B r.f. Service (One Tube)	
		Grid Driven	Grounded Grid
Plate Voltage	1250	1250	1250
Grid Bias	0	0	0
Peak Grid Voltage	175	88	88
Zero Signal Plate Current (ma.)	54	27	27
Max. Signal Plate Current (ma.)	350	175	175
Load Resistance (ohms)	9200	4600	4600
Max. Signal Grid Current (ma.) (1)	26	13	13
Power Output (watts)	310 (2)	155 (2)	141 (3)

(1) Varies from tube to tube (2) Computed power output (3) Measured output (including circuit losses)

The operating parameters of a class B amplifier stage remain the same regardless of whether the tube functions in audio or r.f. service. Grounded grid operation is similar, except that the exciter must supply additional feed-through power required by this configuration. Since class B audio service requires two tubes, all currents and plate load resistance must be halved for single tube r.f. service. Class B audio data is readily available for most tubes and can be used for r.f. service, as shown above.

Figure 2

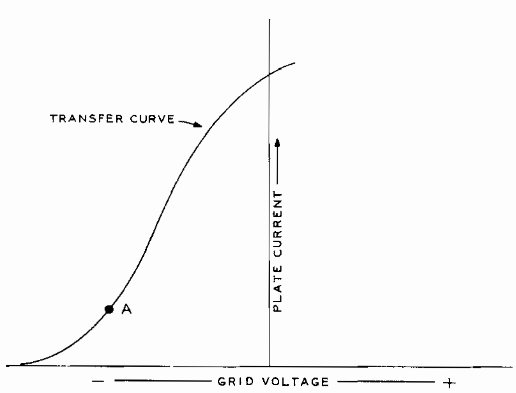
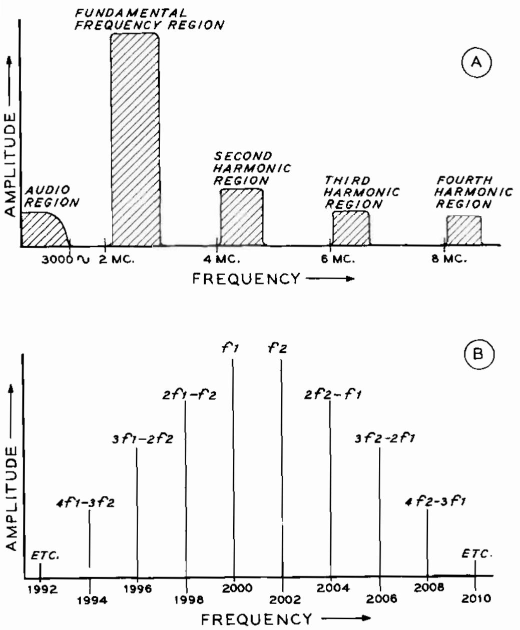


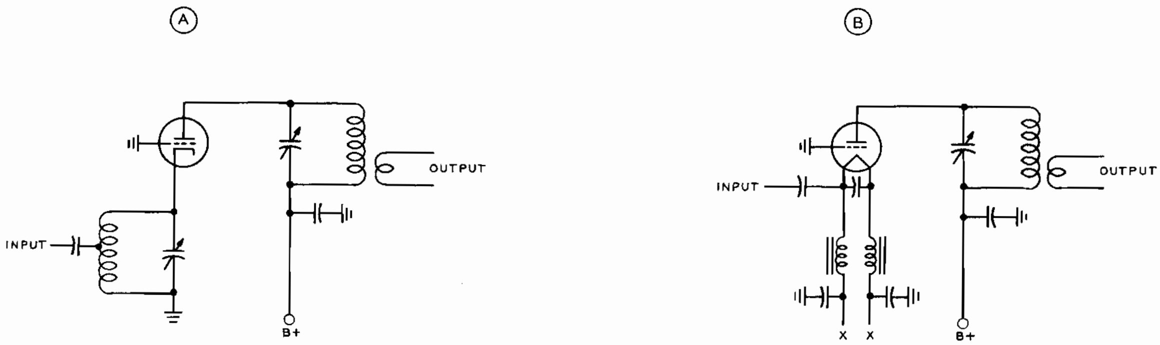
Plate current vs. grid voltage curve (dynamic characteristic) of a vacuum tube. This curve is linear in the center portion and exhibits deviations at either extremity. The shape of the curve and the choice of the zero-signal operating point (A) will determine the distortion produced by the tube. Mixing action caused by nonlinearity produces distortion products which cannot be eliminated by the tuned circuits of the amplifier.

Figure 3



Intermodulation (mixing) distortion caused by nonlinearity is illustrated by two-tone test signal (f_1 and f_2). Even-order products (A) are substantially eliminated by the tuned circuits of the amplifier, but odd-order products (B) fall within the passband of the tuned circuits and are not removed. (B) shows the mixture of spurious signals that make up distortion products falling within the fundamental range.

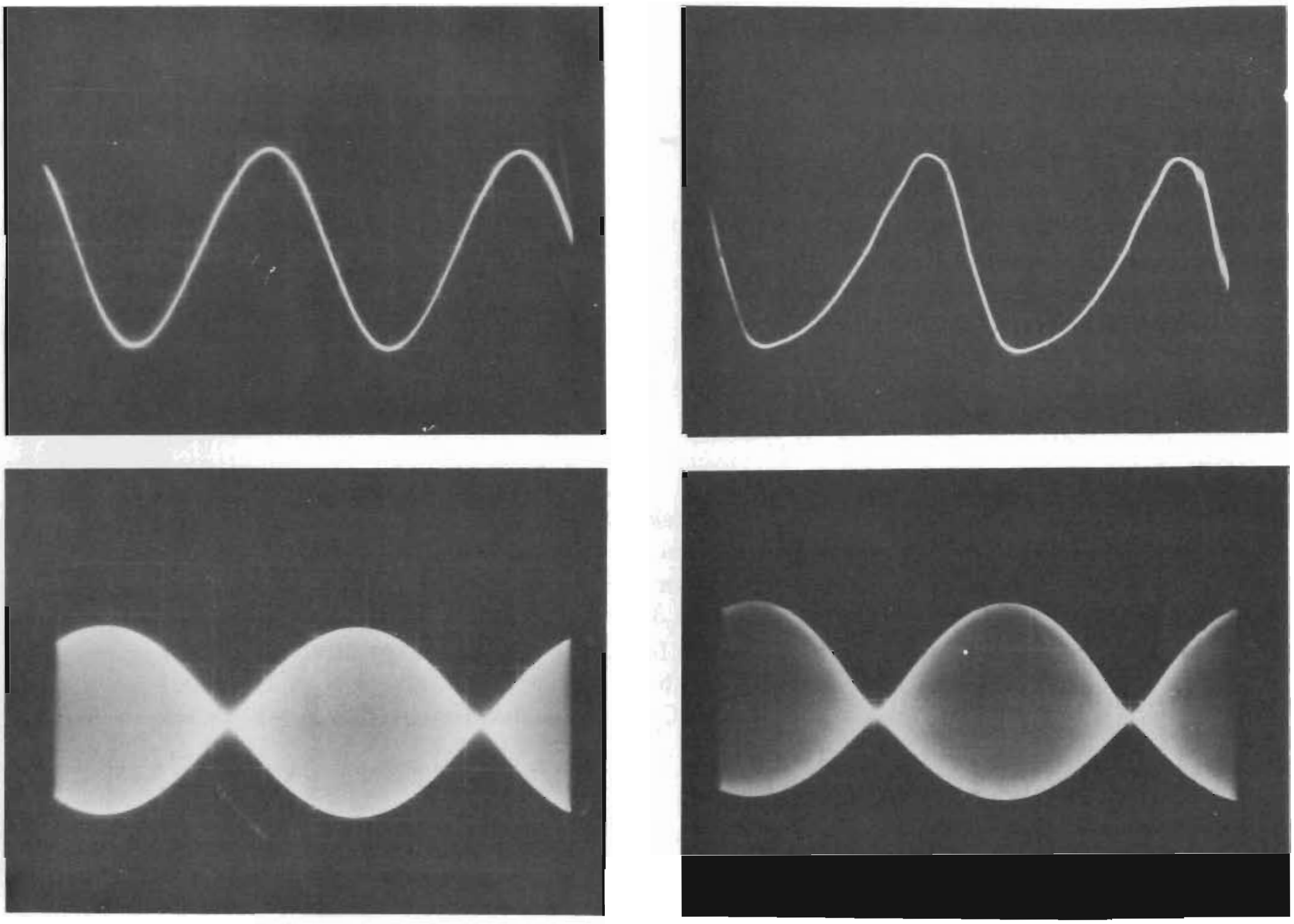
Figure 4



4(A) The grounded-grid amplifier has the input circuit between cathode and ground. The control grid acts as a screen between the plate and the cathode, making neutralization unnecessary in most circuits. The input and output circuits are in series and a portion of the input power appears in the output circuit. The driver stage for the grounded-grid amplifier must be capable of supplying normal excitation power plus the required feed-through power. High-C cathode tank preserves waveform of input signal and prevents distortion.

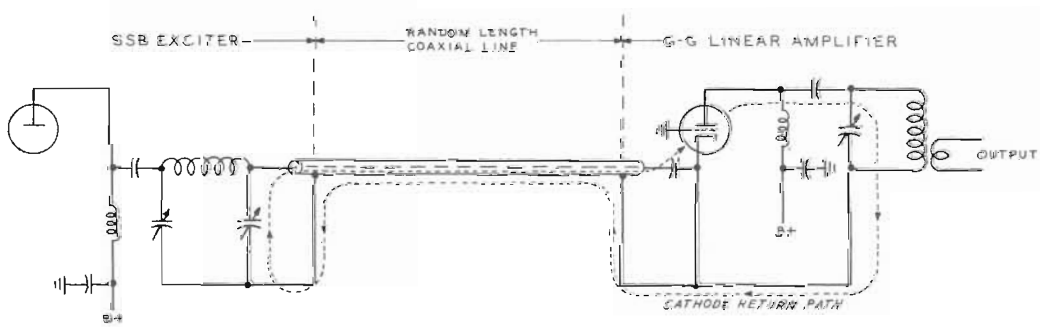
4(B) Popular amateur-style grounded-grid amplifier uses untuned filament choke in place of cathode tuned circuit. Laboratory tests showed that this simplified configuration produced higher intermodulation distortion products and had less power output than the "classic" circuit of Fig. 4(A), regardless of the type of tube used. In addition, the untuned input circuit proved hard to match and drive with pi-network sideband exciter.

Figure 5

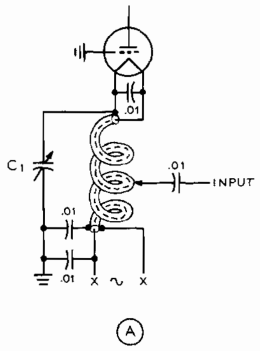


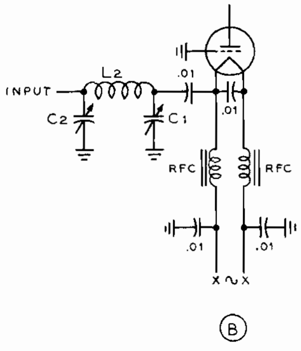
Waveform distortion caused by half-cycle loading at cathode of grounded-grid amplifier can be observed in oscilloscope studies. Lower left: Two-tone test signal when tuned cathode circuit is used. Upper left: 3.5-Mc. waveform (single tone) from sideband exciter as seen at cathode tank. Lower right: Two-tone test signal when untuned cathode circuit is used. Upper right: 3.5-Mc. waveform (single tone) from sideband exciter, showing severe distortion of waveform when untuned cathode circuit is used.

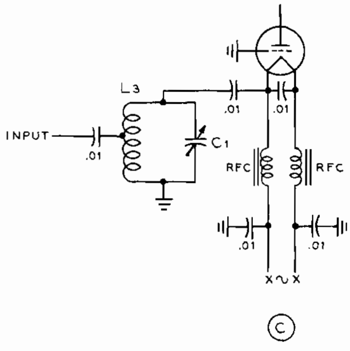
Figure 6



Untuned filament circuit of grounded grid amplifier offers a high impedance to the r.f. current path from plate to cathode of the amplifier tube. The alternative path is via the interconnecting coaxial line and tank circuit of the exciter. Lack of tuned circuit at the cathode of the g-g stage permits waveform distortion of the driving signal resulting in a higher degree of intermodulation distortion and reduced power output.







Tuned cathode network for zero-bias tube may take the form of bifilar circuit (A), pi-network (B), or a shunt LC circuit (C). A Q of 5 is recommended for optimum results. However, as this leads to rather bulky circuits at the lower frequencies, the Q may be decreased to 2 or 3 without serious effects. Capacitor C_1 is a 3-gang broadcast-type unit. Coils L_1, L_2, and L_3 are adjusted to resonate to the operating frequency with C_1 set to about 13 $\mu\mu$f per meter of wavelength. Capacitor C_2 is approximately 1.5 times the value of C_1. The input tap on coils L_1 and L_3, or the capacitance of C_2 are adjusted for minimum s.w.r. on the coaxial line to the exciter.