GRID LEAK DETECTION IN THE 1920s

Dr. H Holden 2001.

Background

The inspiration for this analysis of grid leak detectors came about after reading D. K. Owens' excellent original article in the Feb. 2000 issue of *The OTB*. His article involved the evaluation of the effect of tube bias conditions on the 200-A and 201-A detector tubes.

Having recently acquired my first 1920s receiver (a Grebe MU-1), I was very interested to examine the function of the detector, and specifically the effects of using different values of the glass/carbon grid leaks. A number of manufacturers made these in the '20s and the user had the choice of many different brands and values. Much like tubes of the time, these were marketed with very colorful advertising and promises of superior performance.

The question is "How and why do different values of grid leak affect the fidelity of the signal?" This analysis reveals some startling features of the typical 1920s designs.

Understanding AM Detectors

As is usual the best place to start is at the beginning, with the simplest detector circuit, see Fig. 1. This arrangement is the familiar half-wave circuit. Positive peaks of the RF carrier voltage cause diode conduction and the capacitor, Cl, is charged, discharging between the peaks via the resistor, Rl.

Between the positive peaks of RF carrier, the diode is reverse biased. The RF voltage can be represented graphically (Fig. 9). The output from this detector tracks the envelope of the positive half cycles of the RF carrier, and the voltage developed across R1 and C1 is the recovered modulation, called +DET or positive detection.

With proper proportioning of values the signal has the serrated character illustrated in Fig. 10. Between the positive peaks, the detected signal falls away exponentially as the capacitor discharges via the resistor. This voltage is "updated" on the crest of each succeeding cycle of the RF carrier (shown as the dotted lines under the recovered signal for illustrative purposes).

If the diode is reversed as in Fig. 2 then this is negative detection, -DET, and the negative envelope of the RF signal is detected as shown in Fig.11. This is just as satisfactory, since the AM carrier is symmetrical about its zero axis. This -DET circuit can easily be evolved into the grid leak detector circuit as will be shown. However in the analysis of the frequency response of the detector the easiest one to use is the +DET due to the positive voltage convention.

Taking the -DET circuit of Fig. 2, we move the earth to a different position, (Fig. 3), and simply re-draw the circuit (Fig. 4). Now the voltage with respect to the earth or ground connection (measured across the diode) is a combination of the RF carrier and the detected voltage across the resistor and capacitor. This is represented graphically in Fig. 12.

Using a good silicon diode and efficient detection, the positive tips of the RF carrier get "clamped" a diode voltage drop above ground. Tube diodes are resistive and the "clamping" is less effective. The carrier peaks rise up above the reference level when the carrier amplitude is higher, to some level, as indicated by the dotted line on Fig. 12.

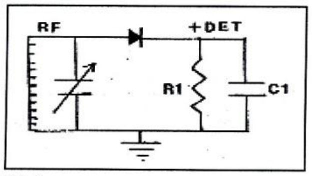


Fig. 1.

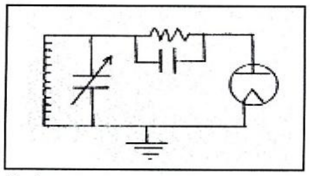


Fig. 5.

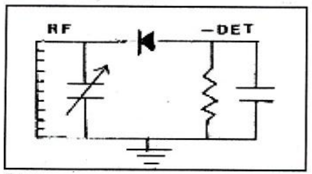


Fig. 2.

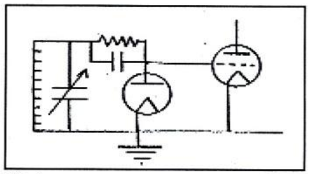


Fig. 6.

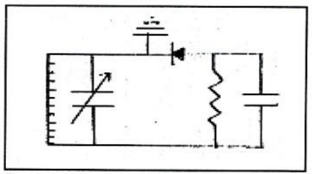


Fig. 3.

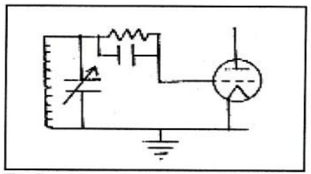


Fig. 7.

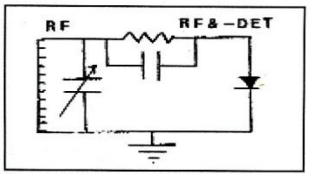


Fig. 4.

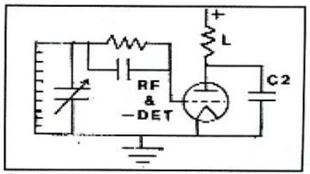


Fig. 8.

Fig. 9.

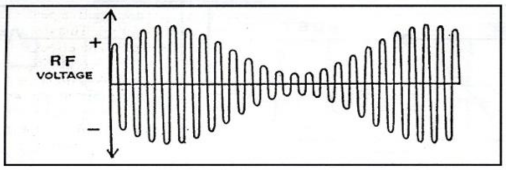


Fig. 10.

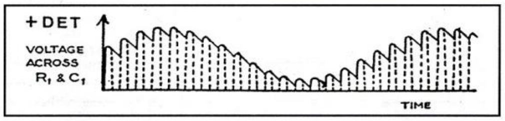


Fig. 11.

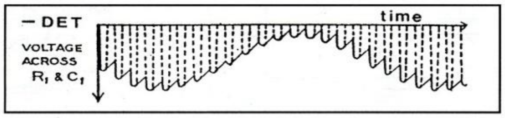


Fig. 12.

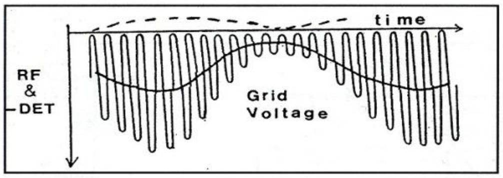


Fig. 13.

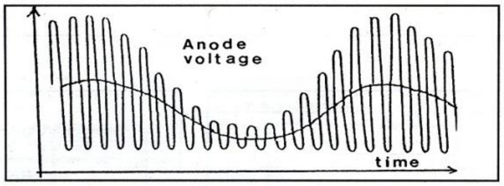
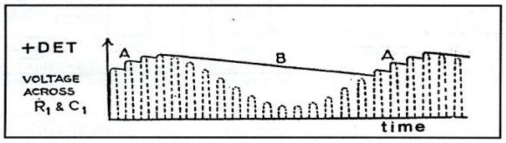


Fig. 14.



The detection is less efficient on account of this; and the demodulated signal amplitude is reduced, however, it still works. The solid line in Fig. 12 represents the DC axis of the signal for illustrative purposes only, and as can be seen this is the recovered "modulation." This is essentially the signal present at the grid of a grid leak detector.

Moving on to Fig. 5, the semiconductor diode has been replaced by a tube diode, and in Fig. 6 an amplifier has been added. The amplifier's grid/cathode behaves as a diode, so you can remove the original diode (Fig. 7), and the circuit function is the same, assuming of course that the grid/cathode is as efficient as the original tube diode, which for practical purposes is reasonable.

However the effective diode function is moderately resistive. In circuits Figs. 4 through 8, the resistor can be returned to the opposite side of the tuned circuit with minimal effect except that the capacitor's discharge pathway includes the RF coil.

The tube's grid voltage (again see Fig. 12) results in changes in the tube's anode current, so a voltage is developed across plate load L (Fig. 8). Again an RF voltage (Fig. 13), which is amplified and 180 degrees out of phase, appears on the plate. Again the solid line in the graph of Fig. 13 represents the DC axis of the signal, or the average value. So when the RF carrier is filtered off the plate by C2, the modulation is recovered.

The Grebe MU-l has a very satisfactory arrangement here; the plate load is the primary of a 1:5 ratio transformer with an grounded core. In addition, the transformer has no response at radio frequencies. The residual RF not fully filtered off cannot pass to the secondary. In addition, the audio voltage is stepped up by a factor of 5 to drive the grid of the first audio stage. So the transformer performs two functions. This should not be forgotten when one considers replacing a failed transformer with an RC network. A substitute RC network cannot duplicate this exactly.

Frequency Response of the Detector

If the product value of Rl and C1 (i.e. the time constant) is too long, then distortion results in the detected waveform. In general this takes the form of negative peak clipping of the recovered modulation. This occurs with the high frequencies first. The effect is to degrade the clarity of the audio, producing a "woolly" or "muddy" sound. This is illustrated in Fig. 14, region B.

During this period the diode is reverse biased and Cl discharges via Rl with the familiar exponential waveform. Regardless of detector efficiency, i.e. various tube types, diode or grid/filament of triode, or semiconductor, the behavior of the circuit, between RF voltage peaks, is independent of the diode and dependent on the RC network. It is the analysis of this RC circuit that is important in determining the detector function.

I found it necessary to devise a way to predict the upper frequency that a particular RC filter could support without distortion, and the results are quite remarkable when one considers common values used in detector circuits of the 1920s.

The value of the capacitor associated with the leak is chosen to be relatively large with respect to the tube's (or diode's) input capacity, but not so large that too small a value of grid leak resistor is needed. The lower the value of R, the heavier the loading on the driving tuned circuit.

Also, the efficiency of detection drops due to the diode's forward resistance when the resistor is too low in value. Typical capacitors for this purpose range from 100pF to 250pF (100pF is the superior value). This leaves one with the value of the grid leak to determine the circuit performance. Again this was a "user" variable in the 1920s.

The ability of the detector to resolve higher audio frequencies without distortion depends on the value of Rl and Cl and the depth or extent of modulation. Negative peak clipping, if it is going to occur, will always be worse with heavier (deeper) modulation. We need to be able to calculate the maximum allowable value of grid leak resistor, and the associated capacitor, before negative peak clipping and distortion of the higher audio frequencies occur.

After consulting a number of texts, including Terman, it was clear that the formula was not easily forthcoming. Therefore I have solved the problem using two methods, also there is a third way that can be deduced from a concept presented by Terman.

Three Ways to Find the Answer

1) Fig. 15 shows a hypothetical wave of audio modulation of an RF carrier, rising 31.5% above its resting level R (no modulation) to Vp and falling 31.5% below resting level. Therefore the RF carrier on its positive half cycles troughs down to 37% of Vp on account of the modulation. This value has been chosen deliberately to simplify calculations. If we look at the exponential decay of the voltage on an RC network starting from point Vp, so that it falls fast enough so it is below or equal to the trough in the modulation half a cycle later (see Fig. 16), the values are easily calculated. This is because the time taken for an exponential to decay to 37% of its starting value is the "time constant" equal to R times C. So we can conclude that, provided the RC value is equal or less than half the period of the wave, T/2, or put another way 0.5 divided by the frequency, f, then negative peak clipping will not occur. This relation is then, f=0.5/(RC) where f is the maximum allowable modulating frequency. This is a very good approximation, but not entirely accurate as it slightly overestimates the allowable frequency. As can be seen, the exponential is not quite rapid enough to track the faster falling part of the modulating wave.

2) Fig. 17 shows a better way, a cosine wave of modulation, rising and falling one volt above and below its resting value, which is 2 volts above zero. This could be described as 50% modulation. The rate of change with time of this modulating wave at its most rapid part, one quarter of its way into the cycle, an angle of pi/2 radians, can easily be found by taking the derivative of the cosine function and finding the value at that point. The functions and their derivatives are in the table, Fig. 18. Likewise if we consider an exponential starting to fall from the same point (quarter of the way into the modulating cycle) from its timing t = 0, toward zero, which is two volts away, we have the exponential function shown as the dotted line in Fig. 17. We can easily calculate the rate of change of this function by the derivative, see the table of Fig. 18 again, and determine the value at t=0 for this exponential. See Fig. 19 where these two rates of change are calculated. If we make them equal, then the exponential decay of the grid leak capacitor charge via the grid leak resistor is just "fast" enough to track the modulation. This is done in Fig. 20, and the value we get is f= 0.32/(RC).

3) A third way to calculate this is from information provided by Terman about AM detection, p. 555. Provided that the AC impedance (to modulating frequencies) divided by the DC impedance of the detector load is greater or equal to the modulation, m, and that this rule is not violated, then distortion (some form of negative peak clipping) is avoided. "m" is defined as the crest of the modulating wave rising above the no modulation level, divided by the no modulation RF level. For the wave illustrated in Fig. 17 then m = ½ or 0.5. This gives an even more conservative result. It can be calculated from RX/(R[square root of(X squared plus R squared)]) equals m. This is the ac impedance of R and C in parallel, divided by the DC impedance R, where X is the reactance of C. If we make this equal to 0.5 (50% modulation), I calculate the formula to be f= 0.275/(RC). This clearly ensures that the time constant is fast (short) enough to track the modulation without ever ending up with the situation illustrated in Fig. 14. It is interesting that for m=1 or 100% modulation, the equation can't be solved for a value of R, which would have to be zero to satisfy the conditions. This means that with these diode and "RC" styles of detector, that 100% modulated waves, with practical values of R and C, will suffer from some distortion. This is because the RC discharge cannot be made to fall to zero in a sensible time period, as it is an exponential. Modern precision detector techniques get around this problem.

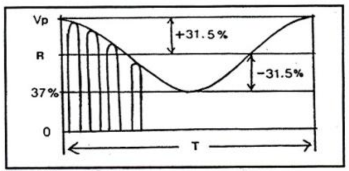


Fig. 15.

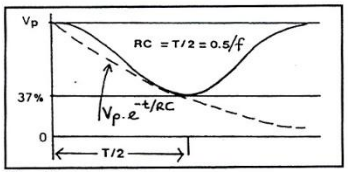


Fig. 16.

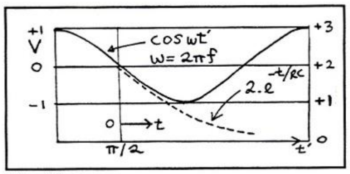


Fig. 17.

FUNCTION	DERIVATIVE
$\cos \omega t'$	$-\omega \sin \omega t'$
$2.e^{-t/RC}$	$-\frac{2}{RC}.e^{-t/RC}$

Fig. 18.

When $\omega t' = \pi/2$, then

$$-\omega \sin \omega t' = -\omega = -2\pi f$$

At angle $\pi/2$, $t = 0$ for the exponential:

$$\frac{-2}{RC} \cdot e^{-t/RC} = -2/RC$$

Fig. 19.

The practical reality of a directly heated tube diode (or triode used as a diode) throws in some interesting features. We can model this as a group of diodes (or grid/cathodes of triodes) and a voltage divider representing the tube's heater element. The heater element (filament) has a voltage distribution. See Fig. 21. When the RF circuit (and grid DC return) is to the positive side of the heater, then diode Dl has no forward bias, D2 a little and D5 has a good forward bias equal to the heater voltage. Forward bias is helpful. "The higher the plate potential, the less is the tendency for electrons to remain in the space charge region (near the "cathode") and repel other electrons." (RCA tube manual, section on diodes). Forward bias assists diode (detector) conduction and function at low RF signal levels. Good detector diodes like the 6AL5 have closely spaced electrodes that minimize the space charge, and rarely need a forward bias. Widely spaced elements such as the grid/filament of a 201A are not as good. Those of us who have tried to use a tube diode in a crystal set in the past know that they don't operate well without some forward bias because the signal level in this application is too low. Possibly though, this "more sensitive configuration" would be prone to overloading with stronger signals.

On the other hand, if the return is to the negative heater, then the imaginary diode elements D2 to D4 have increasing reverse bias. So this arrangement would probably handle higher input RF levels without overloading, but be less sensitive to weaker signals. The results (D.K. Owens' article in the Feb., 2000 *OTB*) with the grid return to negative filament are poor with the 201A.

Weak Signals

It is still possible for the 201A tube detector stage to detect/demodulate AM even with a poor rectification effect at the grid. As long as there is some asymmetry produced by "diode" type conduction, then audio will be retrieved when the RF is filtered off the plate circuit. Anode bend detectors preferentially amplify the positive half of the carrier by being deliberately biased to produce this effect, while an efficient grid leak detector amplifies what amounts to a "voltage doubled" negative half of the carrier. The curved grid voltage versus anode current relationship of the triode can favor "anode bend," however in the boundary between "grid leak"' and "anode bend"' processes, no demodulation can occur.

We can now incorporate a model of a directly heated triode, like a 201A. This could be composed of multiple indirectly heated tubes with their cathodes distributed along a heater chain. Three tubes are shown for convenience (Fig. 22). However we could imagine larger numbers. It now becomes clear that the choice of the grid leak return has two fundamental effects. Firstly it configures the grid/cathode or "diode" component of our triode for generalized forward or reverse bias, and secondly it changes the triode's operating point via the average grid bias. This shifts the transfer function of the tube (change in grid voltage vs change in anode current) to a different part of the triode's curve. The placement of the ground, or "earth connection" either to plus or minus filament, is academic, as the anode current, Ia, is very small with respect to the low resistance of the heater element in the tube. So you can ground either the plus or minus side of the heater in this example with no other effect.

Summary

Let's look at some values of R and C in AM detectors. Values typical in the post war period (*RCA Handbook*) are typically a C of 100pF and an R of 250K. Using my second formula you get f=12800, or 12.8kHz, which is the upper audio frequency you could demodulate without distortion when the modulation is no greater than 0.5. An even shorter time constant is required if the modulation is deeper. This seems sensible, and you'd get pretty good fidelity out of an AM detector for typical voices and music. But what about a grid leak of 3meg and a 100pF capacitor in a 1920s radio? This gives about 1 kHz being the upper frequency you can demodulate without distortion. Combinations such as 3 meg with 250pF are obviously poor. I suspect that with a good grid leak of 1 meg, and a 100pF capacitor, then "f max" without distortion = 3.2 kHz. This is acceptable for a horn speaker with a metal diaphragm. It explains why there is a noticeable performance change with different grid leaks, and why users must have liked to try different values. After all many sets did not have tone controls.

Lower values of leak load the resonant circuit driving the detector and lower the gain by: 1) resonant circuit loading, 2) dropping detector efficiency, and 3) broadening the bandwidth, however the treble response is much better. Higher values produce more overall volume but a drop in the amplitude and quality of the higher audio frequencies, "treble cut," as demonstrated even above 1 kHz for common values. In these early times I suspect that people had more of a quest for gain than fidelity. The horn speakers were not up to good high frequency responses, but cone speaker technology was improving, and clearly the detector time constants became shorter as fidelity became an issue. I can clearly hear the difference in the tone of the sound when I substitute a 5 meg leak for a 1 meg in my Grebe radio driving an Amplion AR111 horn speaker.

$$-2\pi f = -2/RC$$
$$f = 1/\pi.R.C$$
$$f = 0.32/RC$$

vs

$$f = 0.5/RC$$

Fig. 20.

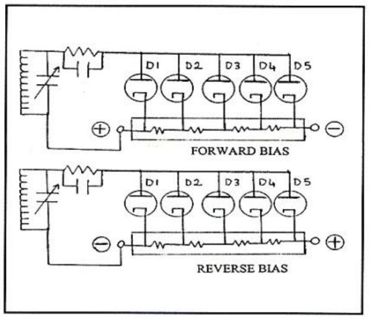


Fig. 21.

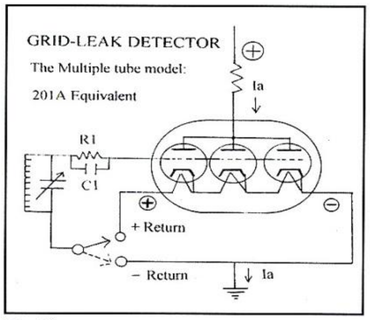


Fig. 22.

From the point of view of detector tube bias conditions, the tube's grid current is so small that leaks ranging from 1 to 10 meg have little effect on the detector tube's bias conditions.

REFERENCES

Terman, *Radio Engineer's Handbook*, First Edition, Sixth Impression, McGraw-Hill, NY, 1943.

RCA receiving tube manual, (post war copy).