Amplitude Modulation ("AM")

using natural asymmetrical voice

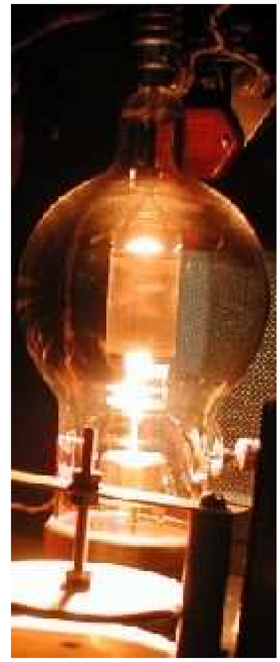
a joint effort by

John, WA5BXO

Bob, WA3WDR (Bacon)

Tim, W5TOB

Don, K4KYV



When I (John) first tried AM, I had a Knight Kit T-60 transmitter, which used controlled-carrier modulation. Controlled-carrier modulation is a method of modulation that maintains a low carrier output until modulation is applied, and then the carrier will increase with the average level of modulation. This is done to keep the power consumption and heat low when you are not modulating. It was often used in rigs that were inexpensive and had components that were not sturdy enough to maintain a higher level of carrier and modulation. Modulation was accomplished by applying audio voltage to the screen grid bias voltage of the RF output tube. Controlled-carrier operation resulted from deliberate rectification of the audio waveform in sections of the modulator that were DC-coupled to the modulator output, and this was arranged to cause the average screen bias voltage to shift upward when audio was present, thereby increasing the carrier level when modulation was present. If this system was not overdriven, the resulting signal was readable, although not pleasing to the listener. The diode detector type receiver's AGC voltage would bump up and down with the carrier shift. This caused a very annoying rise and fall of background noise. Also, with loud speech, the rectifying section of the modulator could easily overperform its function. The resulting distortion was so severe that most of the audio was actually eliminated, just when it should have been the loudest! It was very difficult to avoid overdriving the modulator, without the modulation being too low to hear well. The group of hams that I wanted to join on 3850 KC just couldn't hear me, or complained endlessly about the awful sound from my rig's controlled carrier modulation.

Their complaints were constructive, and they convinced me that I needed to upgrade my modulation technique if I was going to join in the AM fun. My solution was to build a plate modulation system. The modulating audio voltage was derived from an external audio amplifier that could deliver the proper audio voltage to the plate supply circuit of the final RF amplifier. The improvement this made in signal output and audio quality was remarkable. The group could hear me, and hear me clearly. Over time, I learned more, but the knowledge came slowly. It was almost

10 years before I really understood the circuit, and the math behind it. A lot of this understanding is due to my association with Don, K4KYV.

The T-60 was typical of many relatively low-cost transmitters available to newcomers to the hobby in the years from 1960-65, and it is an example of how the manufactures were trying to sell equipment. The advertisements would say something like "Here is a transmitter that will run near the legal limit for a novice on CW and has the capability of running AM when the novice upgrades to general class." The Knight Kit T-60 rig described above was purchased for about $70. The cost of adding the AM capability to the transmitters design was probably about $5. The external modulator that I constructed was built from scrap and hand-me-down parts, but had the parts been purchased, they would have cost more than the Knight Kit T-60. The original $5 modulator that was put into the Knight Kit T-60 was a bungled attempt to add AM capability to a low-cost transmitter, but it sold a lot of transmitters.

Why was screen modulation used? Because it was inexpensive and simple. It did not require any transformers, and only small, low power tubes were needed in the modulator.

Why was controlled-carrier modulation used? Mostly to reduce RF amplifier plate dissipation. Efficiency is low in a screen-modulated AM transmitter. Typical carrier efficiency is only about 35%. The typical 6146B could only produce about 15 watts of carrier power, and at 35% efficiency the plate dissipation was about 28 watts. The thought was to reduce plate dissipation when no audio was present, by reducing the carrier output. Efficiency was lower at lower output levels, but dissipation was lower, too. The idea was that average plate dissipation would be lower, so more carrier power could be produced when audio was present, without overheating the tube. However, the transmitter designs really did not produce much more usable carrier power during modulation, and distortion was so bad that this power seemed higher, but it really did little good.

Some amateurs have made simple improvements to the screen modulator circuitry of the T-60 and similar rigs. Transmit audio quality can be quite good with circuits almost as simple as the one that was originally used. However, the old problem remains: efficiency is low, and power output is relatively low.

Of course, you can get full class C efficiency with high level plate modulation, and the same 6146B can give you about 49 watts of AM carrier output in this mode. But the problem was, you needed a powerful audio amplifier with a modulation transformer, all of which was more complicated and expensive. So, some amateurs had another idea: use a linear amplifier. You could generate AM at a very low power level, using either plate or screen modulation, and amplify the modulated signal up to high power with a simple linear amplifier.

Transmit audio quality can be excellent, and the modulator does not usually require a modulation transformer, but there is a problem. The efficiency of a class B linear amplifier at full output is about 66%. However, when amplifying an AM signal, the carrier output level has to be far below the maximum output level of the linear amplifier, to allow headroom for the positive modulation peaks. At carrier level, the efficiency of a class B linear amplifier is only about 33%. At 33% efficiency, that 6146B can only give us about 14 watts carrier with about 28 watts of plate dissipation. So we were back to the same problem we had with screen modulation: low efficiency, and relatively low power output.

There were some very complicated and exotic modulation techniques available in those days that could produce quality AM at high efficiency with no high-level modulator, but these were so complicated and difficult to tune that they were impractical for amateurs to use.

High-level plate modulation was the way to go. Many high-level plate modulated amateur transmitters were sold in that era. AM operators quickly associated strong signals and intelligible audio with high-level plate modulation of a Class C RF final.

The FCC regulations at the time stated that the general class license holders could run no more than 1000 watts DC input power to the plate circuit of the RF final amplifier. This was easy to measure with DC meters. The plate supply voltage was multiplied times the plate supply current, and the product was the DC input in watts.

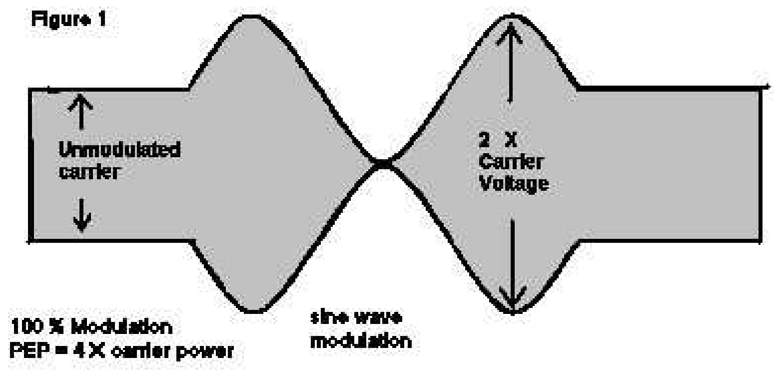
RF amplifier efficiency determined how much output power could be achieved. The efficiency of a screen modulated RF output stage or a class B RF linear amplifier at carrier level is about 33% to 35%, giving you about 330 to 350 watts of carrier output on AM for the maximum legal input power of 1000 watts. On the other hand, a plate modulated class C amplifier has about 75 percent efficiency, giving you about 750 watts of AM carrier output for that 1000 watts input. And the output tube in the final RF amplifier runs a lot cooler in class C than in class B AM linear operation, so smaller tubes can be used. But the only practical way for hams to get high RF amplifier efficiency with AM was to apply the modulating audio voltage to the plate supply of the RF final, and the audio circuitry required to do this must be capable of at least 500 watts of audio. So, to get the extra power output within the legal definitions, most of the big-gun operators opted for the high-level plate modulation method.

The high-level modulation method is the application of the modulating voltage to the plate circuit of the class C final, causing the output amplitude to vary in accordance with the applied modulation. One hundred percent (100%) modulation was generally defined as the point where the maximum modulating voltage, during its negative half cycle, opposed the DC supply voltage sufficiently to reduce it to zero. If this voltage dipped below zero, over-modulation and splatter were the result.

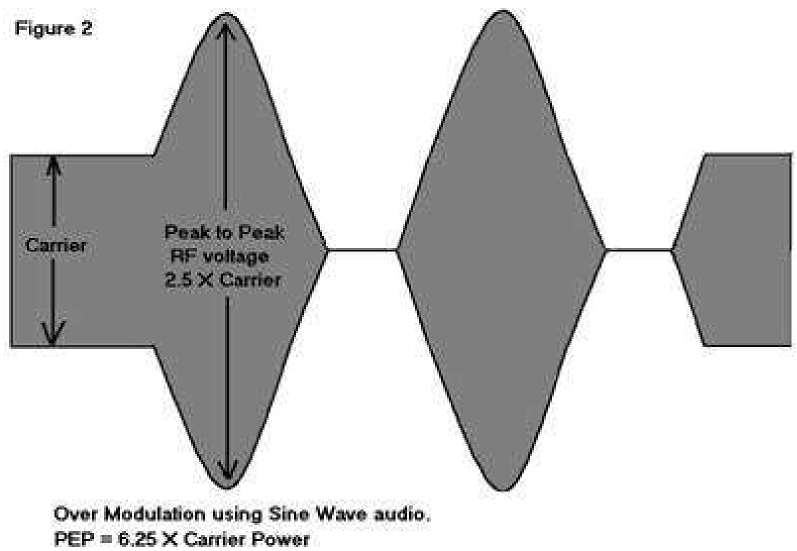
Most people agreed that the peak of the positive half cycle of the modulating audio voltage, added to the DC supply, could go as high as necessary to faithfully reproduce the audio as an image of the microphone output. Even if the positive peak was more than two times the amplitude of the negative peak, the modulation was not considered illegal unless it contained distortion products that caused splatter over an excessive bandwidth. Over-modulation was only considered to occur at the point where modulation characteristic became non-linear, producing distortion and splatter.

The audio voltage from a microphone is often not symmetrical, unlike a sine wave from a signal generator. This asymmetry is a natural quality of speech and other sounds. This article discusses the use of voice waveform asymmetry in AM systems.

When an AM transmitter is 100% modulated by a pure sine wave, the PEP (Peak Envelope Power), is 4 times the un-modulated carrier power. This is because the Audio Voltage modulating the carrier doubles the RF voltage at the peak, since the load resistance is constant, the RF current doubles at the same instant as the RF voltage. Since P = E * I, then P at the instant of the positive peak must be 4 times greater than the power of the original carrier (see Figure 1).



If the transmitter modulation is increased until the peak RF voltage is 2.5 times the original carrier RF voltage, the peak RF current occurs at the same instant, and it is also 2.5 times as great as the original carrier RF current The result is a PEP of 2.5 * 2.5 = 6.25 times the un-modulated carrier power (see Figure 2).



Here's the math:
PEP = ((peak-to-peak modulated RF voltage / un-modulated carrier voltage) squared) * un-modulated carrier power

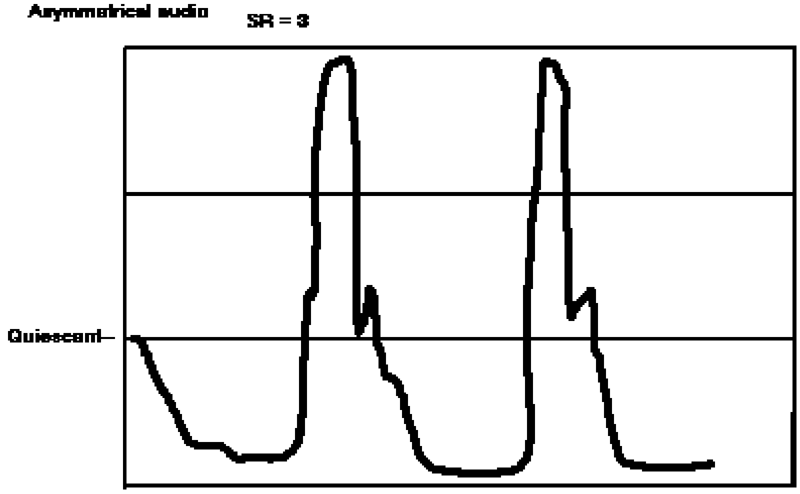
This large PEP can occur without negative over modulation, if the modulating audio is acquired by a voice from a microphone. Microphone audio is generally asymmetrical.

To help me understand and explain the relationship between audio and purity of modulation, I've defined a function, which I call Symmetry Ratio (SR).

Symmetry Ratio (SR) defined:

SR = (Peak-to-Peak audio voltage) / (lesser of the two Peak Audio Voltages above or below the quiescent line)
SR = 2 if the signal is a Pure Sine Wave
SR cannot be less than 2

My typical voice audio waveform acquired from a high quality microphone and measured with a high quality oscilloscope. See figure 3.



While using the quiescent level as reference, note that the positive narrow peaks go twice as high as the negative wide peaks.

SR = (Peak-to-Peak audio voltage) / (lesser of the two Peak Audio Voltages above or below the quiescent line)

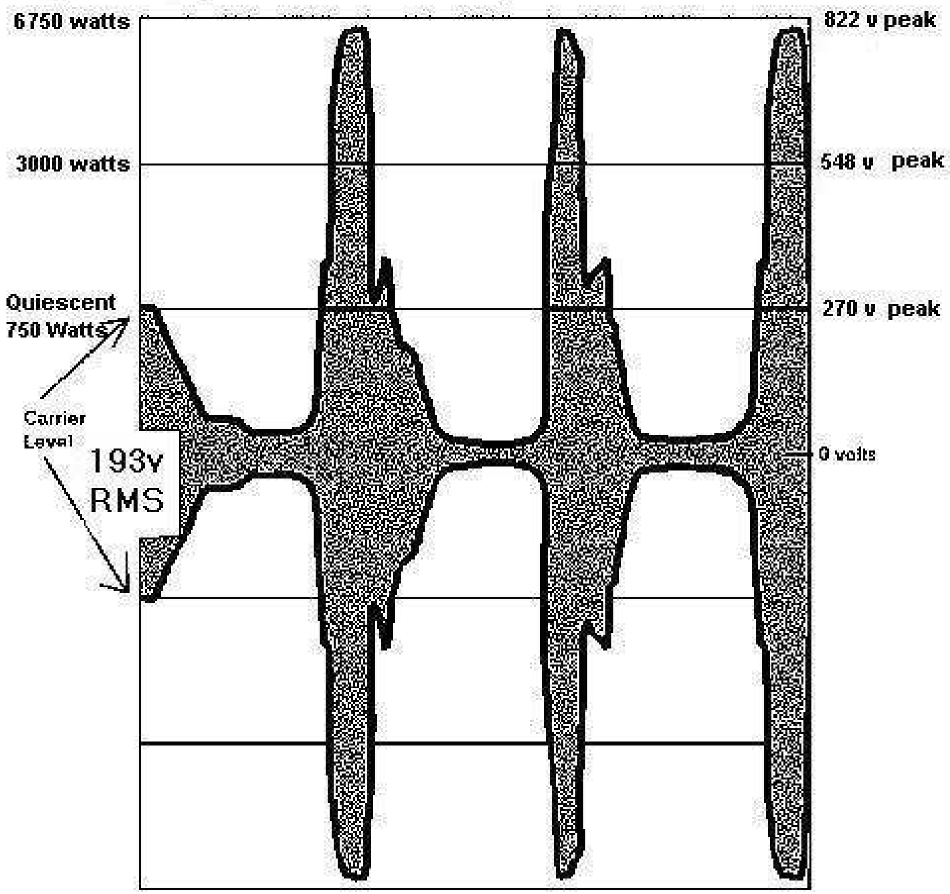
Peak-to-Peak audio voltage = near 3 units

Lesser of the two Peak voltages (negative in this case) = near 1 unit

SR=3

Figure 4 is the RF envelope view that would be produced by modulation with the audio as represented in fig 3. The RF final plate input power is 1000 watts, and the efficiency is 75%. This yields a carrier level of 750 watts as represented at the quiescent level on the chart.

Figure 4 asymetrical audio modulation, no distorion SR=3 50 ohm load



Carrier is 750 watt because of 75% eficency on a transmiter running 1000 Watts DC power input.

Power Increase to the square of the voltage increase. $P=E^2R$

The maximum audio modulator power requirement for 100% modulation of a 1000 watt high level modulated class C final is 500 watts, *but only if the modulating signal is a sine wave*. The reason for this will become apparent from the following example.

The following example will show that the required audio power necessary to achieve 100% sine wave modulation is 50% of the value of the DC Plate input power supplied to the final class C RF amplifier.

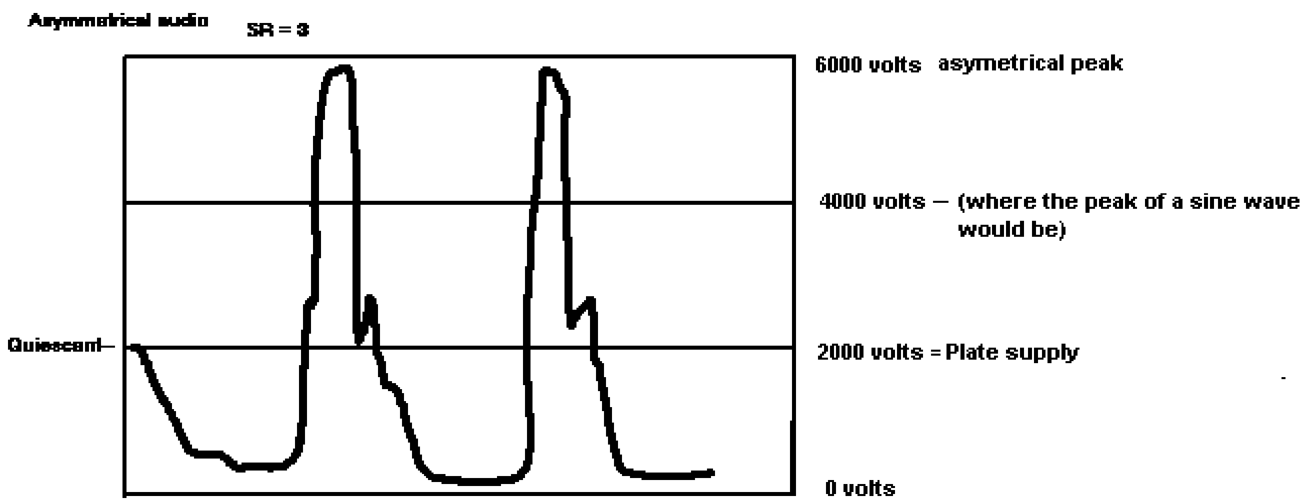
Assume that the final amplifier has 2000 volts applied to the plate with a current of 500ma. This makes the power equal to 1000 watts. To achieve 100% modulation, the peak modulation voltage of the sine wave must be 2000 volts and because of the symmetry of the sine wave will yield a 4000volt peak-to-peak swing (0 – 4000V when the quiescent DC is at 2000V) thus providing the desired 100% modulation. To calculate average power rather than instantaneous peak power we must convert the peak voltage output from the modulator to a “Root Mean Square” voltage (Peak voltage X square root of 0.5 = RMS Voltage). RMS voltage is equal to 0.707 of the peak voltage.

Let’s use this example to illustrate the calculation of the power required for the modulator to achieve 100 % modulation. First the simplest case:

Modulation by a pure sine wave:

Calculation	Equation	Calculation
RMS Voltage	= Peak(volts) * .707	= 2000 (volts) * .707 = 1414 RMS Volts
Load Resistance (modulator)	= Final Dc Plate (volts)/final Dc Plate Current (amps)	= 2000(volts)/0.5(amps) = 4000 (ohms)
Power (modulator)	= RMS (volts) squared /Load Resistance (ohms)	= (1414 Volts) * (1414 Volts) / 4000 (ohms) = 500 Watts

If the modulating voltage is not a pure sine wave (as in our example), then special calculations are necessary – as illustrated below.



Again if the plate voltage on final is 2000 and the current is 500ma then in the above asymmetrical example the peak-to-peak swing of the plate voltage would be (0 – 6000 volts with the quiescent plate voltage at 2000 volts DC). (6000-2000 = 4000 volts peak) This is twice as much peak audio voltage as was needed before. (4000 * 0.707 = 2828 V RMS) and P = E*E/R or ((2828 * 2828) / 4000 ohms) = 2000 watts. Since we have doubled the needed peak voltage, then we have quadrupled the power required to produce it. This does not mean that you will be putting that amount of power into the final continuously, but you will need that capability in order to get the needed voltage swing on the peaks.

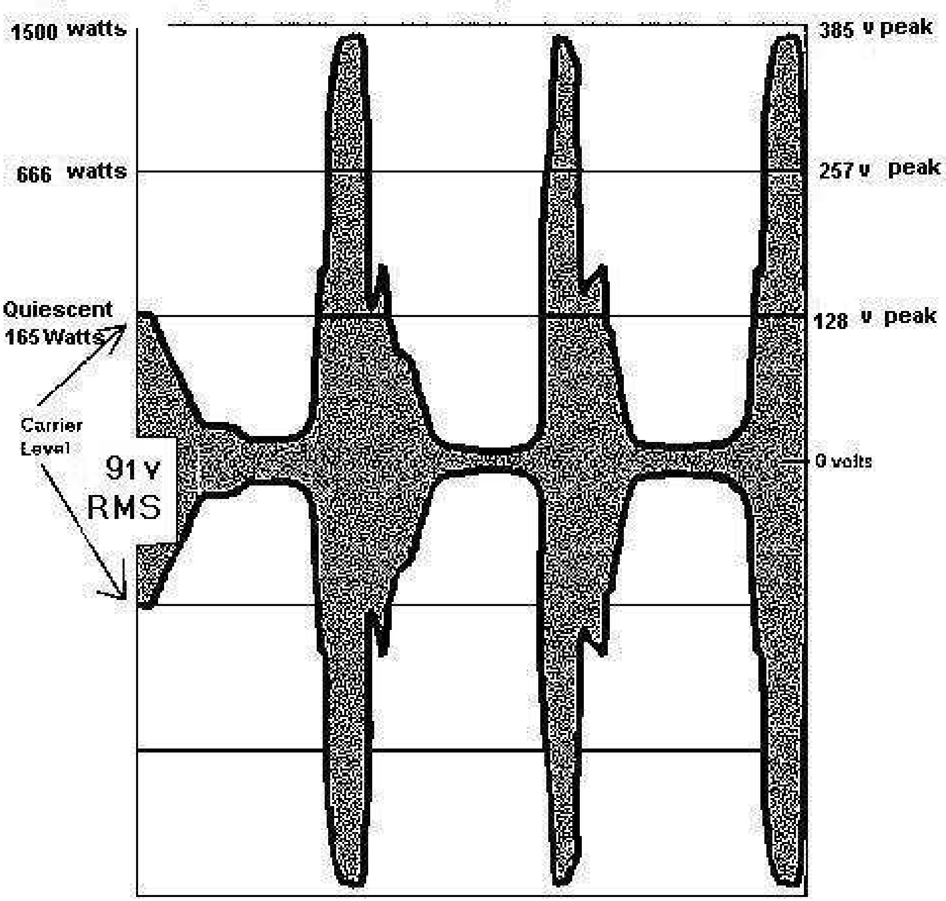
An RF ammeter using a thermocouple actually responds to average power rather than RMS current, because it is heat that causes the indication. This type of ammeter does not indicate true RMS current. Because it is calibrated with an un-modulated sine wave signal, it will read un-modulated signal currents correctly, but its reading will be elevated when normal amplitude modulation is present. It will display a current reading equivalent to the RMS current that would produce the same average power as the modulated wave. In fact, the true RMS current of an AM waveform does not change until modulation exceeds 100% in the negative direction, unless there is nonlinearity or some sort of carrier level shift action taking place.

With a 50 ohm load, a 750 watt carrier will cause the thermocouple RF ammeter to read 3.87 amps. If this carrier is modulated 100% by a sine wave, the average power will increase by 1.5 times (the 50% added power comes from the sideband energy created by modulation). The total

average power will be 1125 watts with modulation at 100%. The RF ammeter will show about 4.74 amps, which is the current that would be necessary to produce an un-modulated signal of this power level. If a person's voice is used to modulate the rig, and the modulation envelope looks something like the scope picture in figure 4, you will see approximately the same increase in RF current, even though PEP with voice modulation is 6750 watts, and PEP with sine wave modulation is 3000 watts. This is because the speech waveform is spiky, so its peaks need to be relatively high in order for it to have the same RMS power as a sine wave. With all this in mind, it boils down to the fact that in order to faithfully reproduce my voice with the legal carrier level of the time, it was necessary to have a modulator capable of 2000 watts. Let me say again that I was not putting 2000 RMS watts of audio into a 1000 watt (input power) rig. But if I had not had the 2000 watt modulator, then the peaks of my voice would have been chopped off or clipped, resulting in distortion and splatter.

Now with the 1500 PEP ceiling, I can only legally run 220 watts input and 165 watts output if I want to properly reproduce my voice. See Figure 7 below.

Figure 7 asymetrical audio modulation, no distorion SR=3 50 ohm load

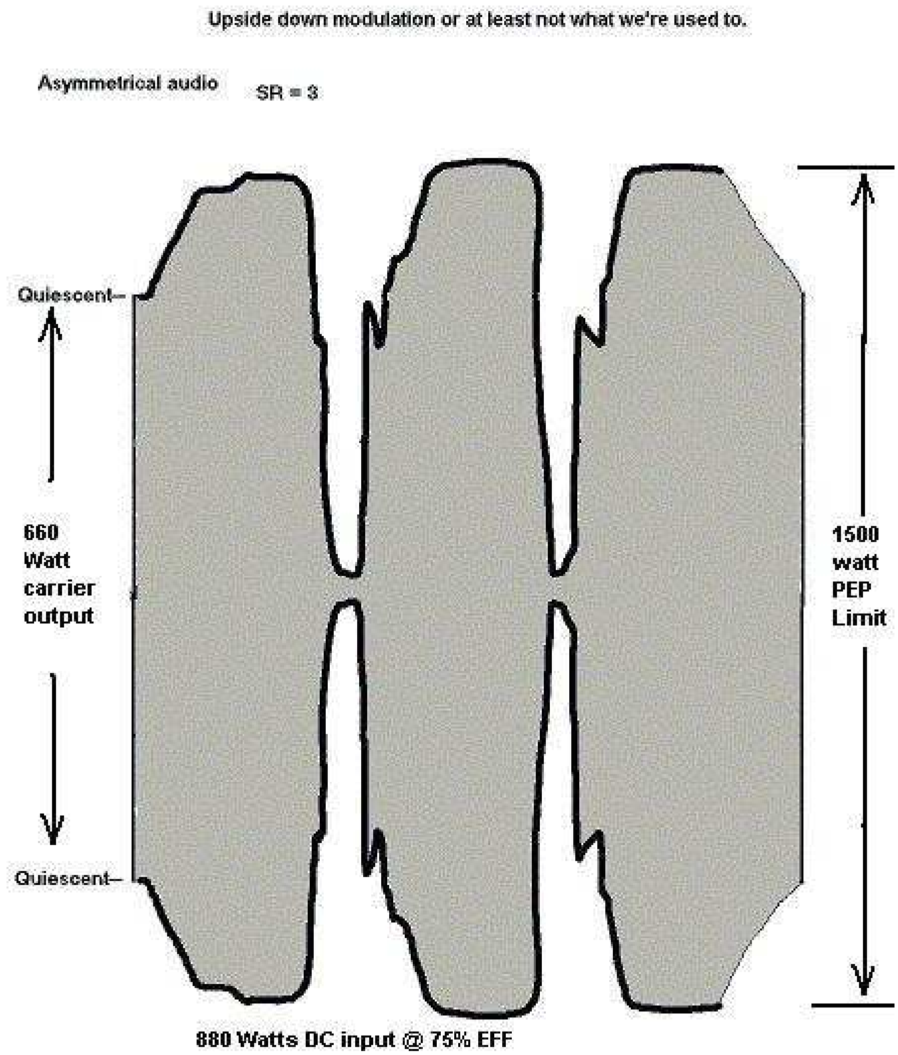


Carrier is 165 watt because of 75% efficency on a transmiter running 220 Watts DC power input.

Power increase to the square of the voltage increase. $P=E^2R$

WELL, with the new rules of 1500 PEP output limit, perhaps I should invert the audio (change the modulator output winding phase 180 degrees or reverse the microphone wiring) so the

spikes point to the base line and the wide lesser peaks go to increase the envelope. With this arrangement one could run 660 watts carrier output and 1500 PEP. See (figure 6)!



The same audio level and PEP, but more carrier!

****

COMMENTS FROM DON, K4KYV

This article effectively debunks the 375-watt myth. A lot of guys seem to think there is something written in the regulations that says AM is limited to 375 watts carrier power. I have had people express surprise and disbelief when I point out that there is no mention of that figure whatever in Part 97. It depends on the waveform of the audio and even such subtleties as the linearity of the modulated stage. It would be educational to show that it is possible to run more than a "KW" DC input and modulate to 100% in the negative direction and see the peak meter hit about 1500 watts, which is about what it would do with typical male voices that tend to have about a 2:1

asymmetrical peak ratio. If the negative peak hits 100%, the positive peak would hit about 50% modulation, which would give approximately the "legal" limit.

I recall in the early days, when I first got a high power transmitter on the air, I didn't even have a monitor scope. I used an 866A with the plate grounded and the filament circuit connected to the final amp HV lead. Normally, as long as there is a positive or zero voltage on the filament, the 866 does not conduct. Whenever the modulation in the negative direction exceeds 100%, it drives the final plate (and thus the cathode of the 866) negative, and the 866 would flash blue as it conducted. I mounted the 866 in a small metal box painted black inside, with a little viewing window. It was easy to see the most minute flash, so it made a foolproof but simple over-modulation indicator. Later, I biased the plate to about +30 volts with a small power supply capable of about 100 mills, using a heavy bleeder to maintain regulation. That allowed the tube to flash just before 100% modulation (also overcoming the +15 volts required to trigger the 866). With the modification, the flash indicated that the transmitter was about to be over-modulated, whereas the original circuit indicated an over modulation condition, after the fact. At the time I wasn't even aware of the natural asymmetry of the human voice.

I am sure many other hams were/are also unaware, and just assumed that if you hit 100% on negative peaks you automatically hit 100% on positive peaks as well, with voice modulation as well as a sine wave tone. So I could have been running my audio either way. I'm sure many cases of unexplained splatter result from the high positive peaks trying to drive a transmitter capable of modulating only 100% positive, resulting in flat-topping, which causes about as much splatter as negative over-modulation. So two hams could each have a KW transmitter modulated 100% as indicated by a negative peak flasher, and one transmitter be will within the limit, while the other kicked the peak meter off scale, and lacking knowledge of the asymmetry factor, be completely baffled to explain why.

As Gary K4FMX pointed out a few weeks ago, the PEP rule actually hit the SSB community about as badly is it did AM'ers, because the rule is based on the mistaken notion that PEP is always double the average power. This is true with a two-tone test signal, but with most voices, the peak-to-average ratio is more like 7 to 10 dB. That's why a VU meter should be driven only up to about 30% on voice peaks while talking, not all the way to the red mark.

Load up a typical table top SSB rig to maximum dead carrier output, and set the ALC threshold just to the maximum power output capability of the transmitter (about 100 watts). Now switch to SSB, and adjust the mic gain so that the ALC just barely kicks on voice peaks. At that point the transmitter is running 100 watts PEP. Now read the average power output with a reliable wattmeter, such as a Bird 43. The voice peaks will not drive the meter to 50 watts as commonly assumed, but more like 10 watts average power. If the microphone gain is turned up so that the average power hits 50 watts, the signal will be severely flat-topped, and splatter will result. This explains why SSB signals have typically been so broad over the years, despite claims of how "narrow" SSB is supposed to be.

The PEP rule had little effect the majority of SSB'ers, who were overdriving their rigs anyway, but someone who had a clean amplifier capable of 3 to 4 KW PEP output could talk the rig up to the old DC power limit, so that the meter kicked up to 1000 watts input on voice peaks. They might be running 3 or 4 KW PEP output, but their signal would be clean and splatter/distortion free, and they would be hitting average power outputs of 300-500 watts output. The PEP rule thus made a clean SSB rig running a KW input just as "illegal" as a KW input an AM. Of course, few amateur linear amps were ever capable of a clean 1500 watts pep, but most hams are unaware of that. The only way you can run SSB within the legal PEP limit and get the assumed 500-750 watts average

power on voice peaks without splatter is to use so much speech processing that the voice signal sounds mushy and intelligible. The typical ham simply overdrives his SSB linear until the meters read a hefty amount of output power. For those concerned over compliance with the rules, overdriving a linear into flat-topping and distortion is just as illegal as running an AM transmitter beyond the 1500w limit, since Part 97 also says that a transmitter must be operated within the parameters of "good engineering and amateur practice". In addition, the FCC is very specific regarding spurious emissions. See Section 97.307(d). If the amplifier was built after 14 April 1977 or marketed after 31 December 1977, the spurs must be down 44.77 dB at 1500 watts PEP

The bottom line is that before the SSB community complains that some AM'ers may be running illegal power with their plate-modulated transmitters, they need to clean their own houses first. And many of the big guns will be disappointed with the results once they do.

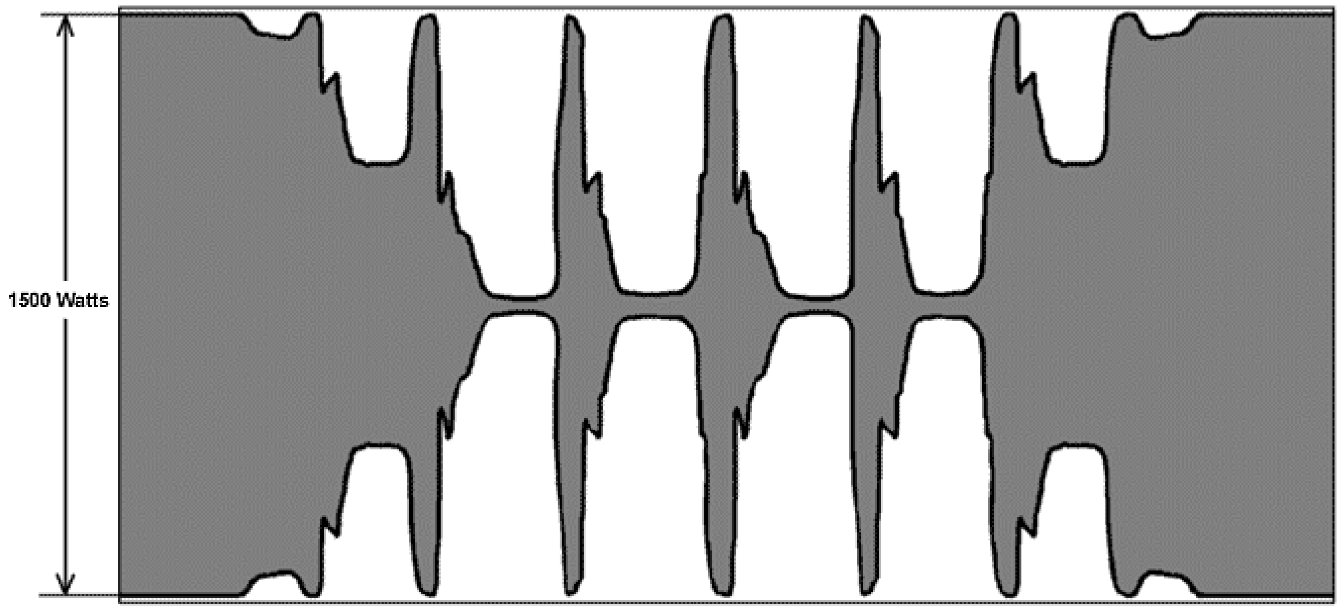
73, Don, K4KYV

****

Comments from Bob, "Bacon", WA3WDR

Reverse carrier control is another way to have more carrier with a fixed PEP.

The usual application of "carrier control" causes transmitted carrier to be reduced during periods of low modulation. But what if we do the reverse instead? What if we increase carrier when modulation is low? Carrier could vary from 1500 Watts with no audio, to 300 Watts or so with full modulation. Peak envelope power would remain 1500 Watts. In effect, we can get 1500 Watts of carrier, and any degree of modulation we want - we just can't get them at the same time. See Figure 7.



REVERSE CARRIER CONTROL - 1500 WATTS CARRIER, 1500 WATTS PEP

With reverse carrier control, there will be a noise reduction effect with receivers having average-AGC (typical of older tube-type receivers), because the elevated carrier will cause their AGC to reduce gain during these quiet periods, and raise gain during periods of heavy modulation. With appropriate audio compression at the transmitter, this expansion at the receiver will reduce background noise without significant audible artifacts. Receivers with peak-sensitive AGC will hold constant gain, which at least will not compress received audio as they usually do.

Reverse carrier control is a natural result of using a fast ALC on an AM linear amplifier. A linear amplifier will operate more efficiently with reverse carrier control, because carrier output is at the full output level.

****

Comments by John, WA5BXO

Perhaps a combination of reverse carrier control and upside down audio would have a less drastic effect on the AGC of the receiver. This could be some real good experimentation.