Single Ended vs. Push Pull: The Fight of the Century

by Eddie Vaughn

If you're familiar with tube amplifiers, you know that the two major methods of power stage operation are single ended (SE) and push pull (PP). As with so many things in life, most people are highly opinionated when it comes to these two choices. While any confrontations between the two camps are less likely to end with blood spilled on the floor than say, vinyl versus digital or tube versus solid state (proponents of SE and PP are, after all, still "brothers in tubes"), their clashes can nevertheless become a bit heated at times. The real danger here exists to that poor, well-meaning soul who enters into the discussion and tries to play the peacemaker by extolling the virtues of each method and proclaiming them equals, which is the "raw nerve" for both camps. When this happens, you'll usually see Camp SE and Camp PP rise up in unison, beat him like a rented mule and toss his limp, lifeless body aside as fodder for the vultures, and then resume hostilities as usual betwixt themselves.

Yes, even among the brethren of The Brotherhood Of The Firebottle, there are many schisms. Paper in oil caps versus plastic film caps. Vintage carbon composition resistors versus fancy metal foils and metal films. Vintage amp designs versus modern amp designs. Grid bias versus cathode bias. And then there are various, very adamant "splinter groups." Here, you'll find the "Power Mongers" branch of the Brotherhood. The Power Mongers drive their gargantuan speakers with behemoth devices that give off an infrared heat signature detectable by satellites, and more closely resemble 800 megawatt nuclear reactors than tube amps. No "girlie man" amps for them! Sadly, many Power Mongers wind up in jail, after finally getting busted for the racketeering and smuggling operations they had operated in order to pay their electric bills.

Then, there are the Old Timers, those easy going, laid back fellows who love to enjoy their music with the "warm and fuzzy" sounds of the bygone Golden Era of Hi-Fi. Old Timer is not an age, it's a mindset. They are some pretty young Old Timers out there, who have usually been accepted into the Brotherhood under the wing of an older Old Timer. Every bit as dedicated as the other splinter groups, Old Timers would rather have their Eico HF-87 than a free lifetime membership in the Ferrari of the Month Club and a date with Norah Jones. Life is good.

Finally, there is the most hardcore sect of the entire Brotherhood, The Triode Junkies, which is further divided into the Transmitter Triode Vikings, the DHT Dandys, the Sweep Tube Ninjas, and the fractional-watt Spudmeisters.

Transmitter Triode Vikings are those aggressive individuals who want to crank it to SPLs that give you a nosebleed, but want to do so with class and finesse. Their way is an iron fist in a velvet glove. They differ from the Power Mongers in that they posess a seething dislike for push pull. As a matter of fact, some Transmitter Triode Vikings began life as Power Mongers, but were lured by the seductive sounds of SET, and became Triode Junkies. They do however still retain some of their old Power Monger ways, and 2 watts just won't cut it for them. Their quest for single ended finesse along with enough power to arc weld often drives them to the brink of madness. They do not at all mind the fact that there is nothing more than a thin ceramic cap standing between them and 1500 volts, neither do they mind a level of radiated heat that would leave even Power Mongers reaching for an asbestos suit.

The DHT Dandys are a crew of refined tastes, who enjoy the finer things in life. They mate their Avantgardes with their $35,000 monoblocks via speaker cables that cost more than the yearly Gross Domestic Product of most developing nations. If invited to their home for a listen to their system, you'll find most of them to be very hospitable and civil gentleman, with all the prim and proper ways of a British butler. Alas, there is the occasional DHT Dandy who can be a bit snobbish about the fact they spent more on their stereo than you did your house, but most are true gentlemen who simply love music. However, the situation can deteriorate very quickly if you mention that your favorite amplifier does not contain a DHT power tube, leading you to be escorted from the premises by some very scary looking bodyguards with large bulges under the torsos of their suits. So please, keep your opinions to yourself, be quick to compliment their system, and even if you do not like the caviar and truffles they offer you, pretend to like them anyway.

Sweep Tube Ninjas are "the thinking man's triode addicts". Cunning and crafty, with a million tricks up their sleeve, they are true to their namesake. Being the thinkers and doers thay they are, they can recite the pinout of every television vertical amplifier tube in existence from memory, and delight in building a chintzy looking amp for less than $250 (including $6 tubes) that will amaze and confound the DHT Dandys by it hanging with their $35,000 monoblocks.

The Spudmeisters are a relatively young group that is small and unique, just like their amplifiers. Their common bond is the spud (one tuber) amp. One resistor, one tube, and one output transformer in the signal path per channel, nothing else. Any more than that, and a Spudmeister will fall to the floor convulsing, ears covered, at the thought of putting anything extra in the signal path to contaminate the signal! Coupling capacitors are the ultimate statement of blasphemy to the Spudmeister. Though they only have one scant watt on tap, they don't seem to mind. It's all about quality, not quantity.

Various individuals within the rank and file of The Triode Junkies belong to a dark, fierce, and shadowy sub-sect, the Triode Zombies, who are the mindlessly dedicated Dark Overlords of the Three Element Tube. People who listen to pentode or ultralinear amps are no friends of theirs and are not welcome in their home. Enough said.

Getting serious for a moment, there are two broad categories that all these sects fall into, whether you're an Old Timer or a Spudmeister. Those two categories are Single Ended and Push Pull. Much has been written on how each works, but very little on their *direct comparison*. So, in this article I'll attempt to bring out the virtues and drawbacks of both single ended and push pull operation, lay them out side-by-side, and try to avoid raising the ire of both Camp Push Pull and Camp Single Ended along the way. Enjoy. :^)

How SE Works

Single ended means just that. In layman's terms, a single power tube does all the work. Actually, SE amplifiers may have more than one power tube per channel (parallel single ended, or "PSE"), but each of the parallel power tubes function exactly alike, and handle the entire AC music signal sinewave form together in unison. In other words, they together function as a single tube. Because it must handle the entire waveform, the SE output stage runs in Class A operating class. This means it is biased so that it conducts plate current throughout the entire 360° of the AC signal cycle, and maintains the tube in a highly linear region of it's operation at all times.

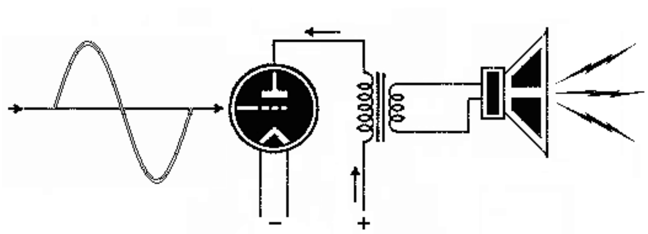

Fig.1 *Single Ended Output Stage*

Fig. 1 above is a typical single ended output stage. This 1940's schematic diagram depicts a directly heated triode, it's output transformer, and the loudspeaker. You'll notice that the single output device handles the entire waveform. As a side note here, some people are shocked (no pun intended) to find out that the music signal in their system is nothing more than an AC voltage, just like your home's AC wall voltage! Depending on where you live, your AC wall voltage has a frequency of either 50 or 60Hz, a single musical tone. The only difference in it and the music signal is that the music signal of course consists of many simultaneous frequencies.

Back to our SE output stage. The reason it must be biased so hot is because of the effect that the AC music signal's negative half-cycle has on the tube itself. Any tube stage must have it's operating point, or "bias" set by making it's control grid some negative voltage value versus it's cathode voltage. This sets the idle point of the tube, or else it would run wide open and quickly burn up. The AC signal's negative half-cycle has the effect of adding to the negative bias voltage present, which reduces current flow just as if you had increased the negative bias voltage. You can think of this as waves in water. Every wave has a crest and a trough. We can liken the crest to our positive AC half-cycle, and the trough as our negative AC half-cycle. The trough is a depression, and when it is added to another depression, the sum result is an even deeper depression! In Class A operation, the tube is biased hot enough that it does not stop conducting current at the peak of the negative half-cycle. If it did, it would not be able to amplify that portion of the signal. It must not only be biased hot enough to merely conduct at the peak of the negative half-cycle, it must still be conducting *enough* current at this point to keep the tube out of the highly non-linear (high distortion) region near it's conduction cutoff (zero plate current). To do so is very inefficient, and Class A's lower distortion and sweet sound come at a high cost of low power, high heat, and faster tube wear.

How PP Works

In push pull operation, two tubes work together as in PSE, but they do so on *alternate* cycles of the input waveform, instead of the *same* cycle. Each tube of the push pull pair bears half of the work, so to speak, instead of SE where any and all power tubes bear *all* the work. To accomplish push pull operation, the tubes of the push pull pair must be fed signals that are in opposite phase to each other, but are otherwise identical in all respects. The "phase inverter" does this. There are several different tubed phase inverter geometries, and each has advantages and disadvantages. Each of them works by splitting the signal into a copy of the original that is in-phase, and a copy of the original that is 180° out of phase. The two phase inverter outputs are simultaneously fed to their respective power tubes. This means the output signals of the power tubes are of course out of phase with one another. They are summed together in the OPT as the signal that drives the speakers. Fig. 2 below illustrates this.

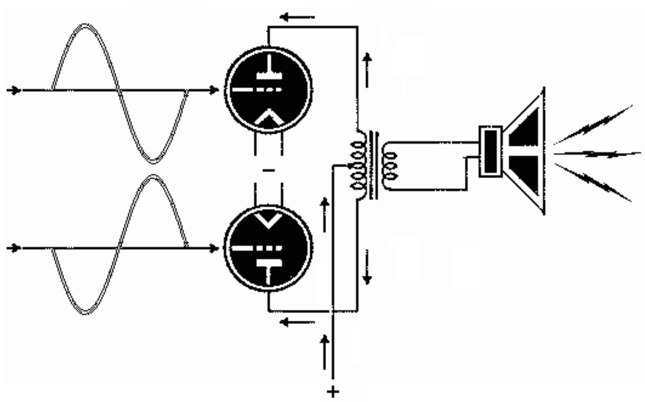

Fig.2 *Push Pull Output Stage*

Note that the input signal going to each tube of the push pull pair is a duplicate of the other, just 180° out of phase, or "inverted phase." You can see how that when one tube is at it's peak conduction when being fed with the peak of the positive half-cycle, his brother across the aisle is chilling out and resting as he is simultaneously fed with the peak of the negative half-cycle. Then, the cycle switches. Without going into a long technical explanation of precisely what happens in a PP output stage, suffice it to say that it does just that, one tube pushes while the other pulls, and back and forth. It can be compared to how SE operates with a very simple analogy.

Think of PP as two men in a small boat, with one rowing on each side. One rows while the other removes his paddle from the water and moves it forward to row again. This motion is repeated back and forth in alternating cycles. Though one is rowing on the starboard side and one on the port side, the sum of their rowing actions is a straight motion. Each expends only half the energy required to propel the boat at a given speed. You can liken SE to only one man in the same boat. He alone not only has to muster the same rowing energy that two men did together, but he must use a lot of his energy in turning his torso from side to side as he rows on each side of the boat in order to make it go straight, wasted energy that does not profit in making the boat move. It is wasteful and inefficient compared to two men rowing together, and the one man is simply not capable of expending the same level of energy as the two men combined are capable of.

Efficiency and Operating Class

Here we see the major reason for using PP, it's high efficiency versus SE. Actually, if the PP topology is ran at the same high current Class A operating point as a SE amp ("high" or "hard" Class A operation), it would produce the same power as a parallel single ended amplifier. No power is gained over PSE by using the PP topology if it is ran in high Class A, because high Class A is so inefficient (typically around 10% efficiency). To capitalize on the power potential of the PP effect, hi-fi gear is generally operated in Class A at a lower current, higher voltage operating point than SE, where the tubes *barely* conduct through the full 360° of the AC input cycle. The need to conduct substantial plate current for the entire 360° is negated by the PP effect, as each tube of the PP pair must handle only half the waveform (180°) anyway, not the entire 360° waveform as in SE operation. This "low Class A" operation is somewhat more efficient and wastes less power as heat, while still maintaining low distortion. Figure 3 demonstrates the opposing phase input signals, and that the tubes conduct throughout the entire 360° of the waveforms.

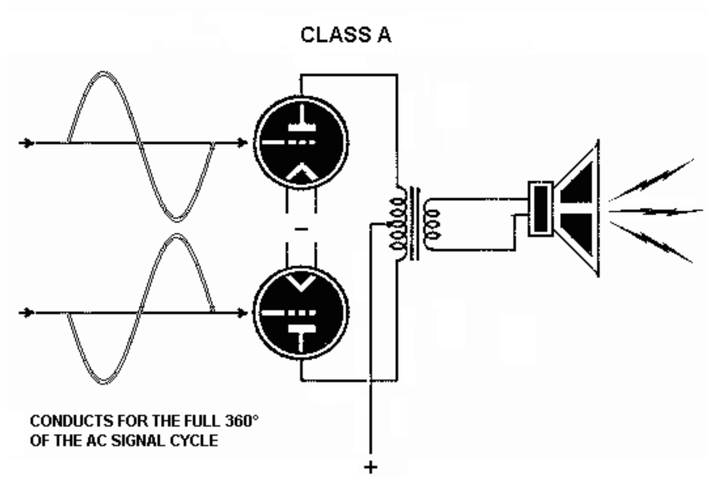

Fig 3 *Power tube conduction of a typical Class A PP output stage*

But if even more power is needed, PP is ran in Class AB operating class to further increase the efficiency. Class AB biases the tubes so that they conduct for less than 360° of the AC music signal cycle, but still more than the necessary 180°, in order to keep them out of the very high distortion region near their cutoff point. Because it idles at generally no more than 70% of maximum dissipation, and conducts full current only on loud peaks at high volume, the tube life is usually longer than with Class A operation. Figure 4 is a representation of the input signals to each power tube of a push pull amplifier in Class AB operation.

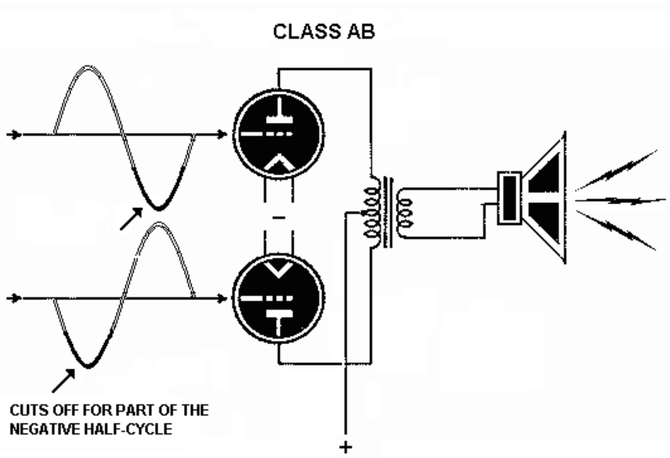

Fig 4 *Power tube conduction of a typical Class AB PP output stage*

Note that in the Class A push-pull amplifier in Figure 3, both tubes conducted throughout the entire 360° of the AC sine wave cycle. In Figure 4's Class AB operation amplifier, the tubes are biased "colder" and conduct for less than 360° but still substantially more than 180°. The black shaded area of the input signal sine wave represents where the tubes cut off on the peak of the negative half-cycle. Because the tubes are wasting less potential power as heat in Class AB than in Class A, the power output is increased substantially. However, due to the lower plate current, they are operating in a less linear region as the postive half-cycle nears the zero (center) line than with Class A. This increases distortion and gives a different sound. This is the conundrum of operating class. When you try for more power, you get increased distortion. When you try to lower the distortion, you lose power.

There are yet other operating classes, but they cannot be used for audio due to their high distortion. Class B operation conducts for exactly half the AC signal cycle (180°), and has extremely high distortion near the center zero line of the AC sine wave. Class C actually conducts for less than 180°. Class B and Class C are used only in RF applications, where the high distortion does not matter. Class AB is so named because it is intermediate between Class A and Class B in function, and behaves in a manner somewhat similar to (but not identical to) Class A at low output. A common urban myth is that "Class AB amps are Class A at low output". This is about as far from truth as it gets. A Class AB amplifier is just as Class AB at idle as it is at full power, and vice versa. As stated, they behave in a manner *similar* to Class A at low output, but they are still running at a Class AB operating point.

Biasing Methods Used in SE and PP

We mentioned bias in our basic primer on SE amplifier theory. Bias is simply making the tube's control grid (where the signal is applied) more negative than the cathode (where the electrons are emitted), in order to set the operating point of the tube. Without it, the plate current flow would be uninhibited and the the tube's internals would melt in mere moments if the circuit's supply voltage was very high at all. Not a happy thing, needless to say. Figure 5 illustrates the two major methods of biasing used in tube amplifiers, grid bias and cathode bias.

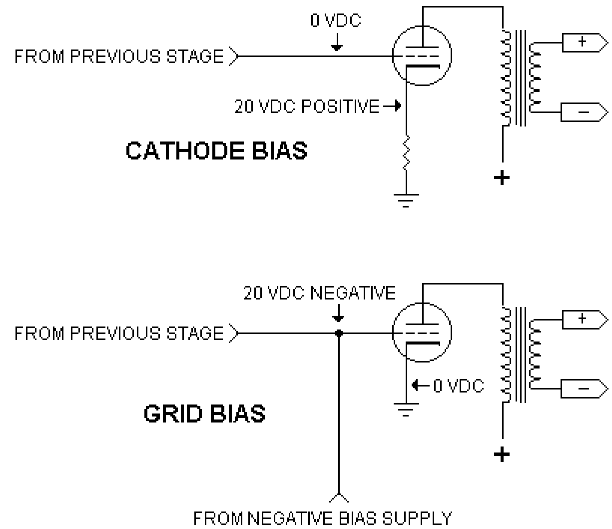

Fig 5 *Methods of biasing a tube amplifier stage*

GRID BIAS – Grid bias (also called fixed or adjustable bias) is achieved by applying the desired negative voltage to the control grid, from a special bias power supply. The cathode emits electrons, which have a negative charge. If the grid is "more negative" than the cathode, it will repel some of the electrons (like charges repel, remember high school science class?), keeping them from leaving the cathode. The higher the negative control grid voltage, the fewer electrons that will be allowed through to the positively charged plate, regardless of the plate's strong, high voltage electrostatic attraction. In Figure 4, we've applied 20 volts negative to the control grid, and the cathode is grounded. The cathode is at ground potential (zero volts), and the grid is 20 volts more negative than the cathode's zero volts, so we have 20 volts of bias.

Grid bias is easily adjusted by varying the applied negative voltage, hence it is often called "adjustable bias." So how can it be adjustable and fixed at the same time? This sounds like a contradiction, but it's really not. It's also called fixed bias because it's fixed to a certain voltage value and does not change regardless of the tube's operation or anything else in the amplifier. It does not mean that it can't be varied if one so desires.

CATHODE BIAS – Cathode bias (also called "self-bias") is a very different method from grid bias, but it accomplishes the same thing. Well, sort of... Grid bias makes the control grid more negative than the cathode. Cathode bias makes the cathode more positive than the control grid, which is exactly the same thing. The grid is still more negative than the cathode, it's just that we achieved it in another way. Remember, in a tube circuit, voltages are relative to *one another* rather than to earth ground. You can see in Figure 5 that the cathode is 20 volts positive with respect to the grid (which has zero volts), so we end up with 20 volts bias.

Cathode bias also differs in that it doesn't use a separate power supply to apply a positive voltage to the cathode, the way that grid bias uses a power supply to give it a negative voltage. The cathode is connected to ground by a resistor of appropriate value, through which it draws it's current. According to Ohm's Law, a positive bias voltage will be created when the tube's current is drawn through the cathode resistor. There you have it, our positive bias voltage is created out of thin air, just like magic, eh? Even neater, the positive bias voltage will regulate itself, unlike grid bias which requires adjustment. If you put in a new tube that draws a little higher than normal current, the increased current draw through the resistor will create a higher bias voltage, shutting down the tube's current draw a bit and forcing it to "chill out." Likewise, a tube with lower current draw will create less bias voltage and allow the gate to open a bit more in compensation.

COMPARISON OF BIAS METHODS – We can see that cathode biasing's self-regulating property tends to prevent or at least alleviate "bias runaway," the condition in which the tube loses bias, conducts wide open, and melts. The more current the tube tries to draw, the higher the bias voltage created to stop it. On the other hand, grid bias can fail and cause the unthinkable to happen. Grid bias failure is caused by a malfunction of the negative bias power supply or the associated componentry that feeds the bias voltage to the tube, or loss of proper contact between the tube socket and the tube's control grid pin due to corrosion, loose contacts, etc.

You're probably asking yourself, "Why on Earth would anyone want to use grid bias, if it requires a separate power supply and can fail, causing a catastrophic, fiery thermonuclear holocaust?" The answer is fivefold.

(1) Grid bias produces more power. All your higher powered push pull amplifiers use grid bias (see below), although it can be used for Class A operation as well, and often is. Cathode bias is less efficient, and wastes some power as heat dissipated in the cathode resistor.

(2) With grid bias, the actual plate voltage of a tube is the measured voltage between the plate and ground. With cathode bias, it's the voltage difference between the plate and *cathode*. Since cathode bias applies a positive voltage to the cathode, the actual plate voltage is the measured positive plate voltage *minus* the positive cathode bias voltage. This means that in many cases, grid bias allows for a lower voltage main power supply than what is needed with cathode bias.

(3) Grid bias *must* be used for Class AB operation. Unlike Class A operation, which draws the same current regardless of signal level, Class AB operation proportionally draws much more current as the signal level increases. The self-regulating property of cathode bias fights against this increase in current. Grid bias works completely independent of everything else in the amp. It's called "fixed" voltage for this reason, remember? This turns out for the best anyway, as the whole reason for using Class AB is for higher power, and as we just read grid bias produces more power than cathode bias anyway.

(4) Grid bias produces lower distortion than cathode bias.

(5) Grid bias allows for ease of experimentation with different plate currents. You can turn the plate current up or down and find the sweet spot that sounds best to you, usually with the ease of turning a trim pot.

Well, now your question has probably been turned around in the opposite direction, and you're asking yourself, "Why on Earth would anyone want to use cathode bias if it wastes power, creates more heat, lacks adjustability, has higher distortion, and sometimes requires a higher voltage power supply? Who cares if it's self adjusting? That's too much compromise for gaining nothing but self-adjustment." The reason is simple. The sound. Cathode bias sounds *very* different from grid bias. Grid bias fans claim their method sounds clean, neutral, uncolored, and firm, while cathode bias sounds soft, mushy, and hopelessly colored. Fans of cathode bias claim their method sounds sweet, warm, musical, and natural, while grid bias sounds harsh, sterile, and artificial.

As we saw, grid bias is always used in Class AB PP amps (by necessity), and in a large percentage of Class A operation PP amps as well. It is even used in some SE amps, but only a few. Most SE amps use cathode bias, which is an essential ingredient of the SET sound. Most people who prefer the PP pentode sound also prefer grid bias, as it tightens and cleans the sound. For what it's worth, the author greatly prefers cathode bias in his hi-fi gear (both SE and PP) and grid bias in his geetar amps. :^)

PP OPT Phase Cancellation

Besides higher output power, PP exercises another huge advantage over SE, which is phase cancellation of certain artifacts. Here's an analogy: If you toss two rocks into a pond at exactly the right time and distance apart so that the crest of one wavefront exactly met the trough of the other, they would cancel each other out. The net result of a crest and a trough together is zero. In other words, the two waves met 180° out of phase with each other, and cancelled each other out. Because of the opposing directions of current flow in the PP OPT, phase cancellation of any "foreign bodies" such as power supply hum and noise occurs. The hum frequency from the power supply enters into the PP OPT's primary winding center taps, flows in opposing directions toward each tube of the push pull pair, and is cancelled by phase opposition. Figure 2 demonstrates this current flow from the center tap outwards. In a SE amplifier, it all goes straight through, and is transferred to the speaker. PP amplifiers therefore need much less power supply filtration to prevent hum that their SE counterparts do. Another benefit of PP is that second order distortion produced in the PP outputs stage is cancelled out in the OPT, which brings us to our next topic:

Harmonic Distortion Series of SE and PP

SE and PP amplifiers naturally produce different harmonic distortion series. Different distortion series sound quite different to the ear. In general, the higher the order, the more offensive to the ear, and in correspondingly smaller amounts with progressively higher orders. Also, odd order harmonics are more offensive up to a point in the series, where it all sounds ghastly horrible in very tiny amounts, whether odd or even order. For example, as much as 3% second harmonic is unnoticed by most people, while .3% (ten times less) fifth order is very noticeable to most people. Second order is manifest as being exactly one octave above the fundamental tone, and therefore it is not dissonant. In small amounts, it is perceived by most ears as adding "sweetess" or "liquidity" to the sound. Third order is a musical fourth above the fundamental tone, which is not terribly harmonious also but not terribly dissonant if held to low enough levels. Fourth order is two octaves above the fundamental, and is not extremely dissonant but blurs focus. Fifth order and up just sounds very dissonant and nasty, period.

A SET (single ended triode) amplifier's main distortion product is second harmonic, which is relatively benign to the ear. The single ended driver stages of a PP amp produce predominantly second order distortion, but the PP output stage itself produces mostly high/odd order distortion. Remember, the second harmonic created in the output stage is cancelled, but any distortion (whether second harmonic or not) produced in earlier stages is passed on through.

The reason why PP and SE output stages produce different distortion series is because they clip differently. This "clipping" occurs when the tube reaches the maximum output attainable at the operating point chosen by the circuit designer. The tops of the sinewave form cannot go any higher (higher amplitude), because the tube is at it's maximum, it cannot amplify any further. Still, on the oscilloscope screen the waveform amplitude tries to grow taller in response the increased input signal. Since it cannot, a flat line appears across the tops of the sine waveform at the "maxed out" point, giving them the appearance of having been clipped off with scissors, hence the name clipping. A PP amplifier clips symmetrically, which means the opposing sides of the sinewave clip alike and at the same time. This produces high/odd order distortion products, which are more offensive to the ear than second order. A SE amplifier typically clips asymmetrically (more on one side of the sinewave), which produces predominantly second order as it's chief harmonic distortion artifact. These different distortion series are one of the predominant reasons as to why PP and SE sound so very different.

Damping Factors of SE and PP

Damping factor is a function of an amplifier's output impedance and how it relates to controlling the loudspeaker, especially at low frequencies. It is expressed as a ratio, calculated by dividing the load impedance by the amplifier's output impedance (Z). For example, if an amplifier has an output Z of 2 ohms and the load is 8 ohms, that gives a DF of 4. This method can be used for estimating the DF, but is not highly accurate. In real life, a speaker's impedance curve is not flat, therefore the actual DF is more or less at certain frequencies. In other words, DF tracks the speaker's impedance curve. When calculating the DF, one must not only figure the output Z of the amplifier's output stage, but must also consider the resistances of the output transformer's secondary winding and the speaker cables as well.

So what does DF do and how does it apply in my system? In general, the higher the DF, the stronger the amplifier's "grip" on the woofer. A low DF makes for tubby, mushy bass with a slow, loose, boomy decay of notes. A high DF makes for better control over the woofer, and yields tighter, drier, faster bass without over-ring and sloppy note decay. A typical SE amplifier using directly heated triodes may have a DF of perhaps 4 or 5 at best. A SE amplifier using triode-strapped tetrodes or pentodes will have an even lower DF, depending on the tube type used. Some have a DF under 2. A vintage PP amplifier from the '60s may have a DF of perhaps 10 or 12. A typical solid state amplifier may have a DF of anywhere from around 100 to over 1000.

MU, TRANSCONDUCTANCE, AND PLATE RESISTANCE – So what does a tube's electrical characteristics have to do with DF? We'll get to that. We saw in the section "HOW SE WORKS" how the plate current and plate voltage of a tube swing up and down, back and forth in a reciprocating fasion in the output stage. The tubes themselves do not amplify, they manipulate the power supply by this voltage/current swing to produce a higher amplitude copy of their input signal across their load. A better term for amplifier would be "modulated power supply" and a better term for an amplifier stage would be "power supply modulator". If there is no load present across the plate of the tube, there will be no amplification. Again, it's *not* the tube itself that amplifies! Back to the voltage/current swing I just mentioned. The plate voltage/current swing occurs in an orderly manner in response to the AC input signal. As we had read in the "HOW SE WORKS" section, on the negative half-cycle of the AC input signal the plate voltage swings high and the plate current low. On the positive half-cycle, the plate voltage swings low and the plate current high. The width of this voltage swing determines the degree of amplification, and the symmetry of the swing determines the orders of harmonic distortion present. It also creates a difference in the DF of SE and PP amplifiers, which we'll see demonstrated shortly.

Let's see how this plate voltage/current swing in response to the control grid signal voltage works to define damping factor. To do that, we first need to look at the three main electrical characteristics that make a given tube type what it is, which are *mu*, *transconductance, and plate resistance*. They are inter-related and inseparably linked. If two of these are known, the unknown third one can easily be calculated.

Mu is the ratio of the change in plate voltage to a change in control grid voltage in the opposite direction, and is usually referred to as the amplification factor of the tube. It's symbol is μ.

Transconductance (represented by it's symbol *Gm*) is defined as the ratio of the change in plate current to a change in control grid voltage. The term "transconductance" is derived from "transfer conductance" and is measured in siemens (S), where one siemens equals one amp of plate current change per one volt of control grid voltage change. It is also commonly expressed as mho, which is equivalent to a micro-siemens (1/1000 siemens). Mho is ohm spelled backwards, which is a very fitting term because conductance and resistance are opposites. A *transconductance amplifier* is an amplifier in which a change in input voltage causes a linear change in output current. Tube amplifiers fall into this category. The other main type of amplifier is known as a *transimpedance amplifier,* where a change in input current causes a linear change in output voltage, exactly the opposite of a transconductance amplifier.

Plate resistance is defined as the change in plate voltage divided by the change in plate current it produces as a result. Plate resistance is expressed in ohms, just like any other resistance. Plate resistance is symbolized by *Rp*.

PLATE CURRENT AND DAMPING FACTOR – We can see how these three parameters are related and interactive. The property of their interrelation we are most concerned with here is how plate current affects plate resistance. Plate resistance drops with an increase in plate current, provided the other variables remain constant. To see how this relates to damping factor, let's build a theoretical SE amplifier and a theoretical PP amplifier, for the purpose of observing how each topology's inherit way of operating affects it's output impedance. Let's use the same triode power tubes in both amps, and run both in hard Class A operation at the same voltage and idle current. Both amplifiers use grid bias, and both their OPTs have the same secondary winding resistance.

Let's power up our SE amplifier first, and give it a signal. Remember, we just read where plate resistance drops with an increase in plate current, provided the other variables remain constant. On the positive half-cycle of the AC input signal, the plate current swings high, and therefore the plate resistance is lower on the positive half-cycle than the negative half-cycle, where the plate current drops. By this, we can see that the plate resistance goes up and down in sync with the polarity swings of the AC input signal. The higher the plate resistance, the higher the output Z, and the lower the DF. Here's where we start getting to the core reasons of why most PP amplifiers have firmer bass than SE amps. The DF flip-flops up and down with each 360° cycle of the AC input signal. This tends to give SE amplifiers an odd bass performance characteristic. The DF is different on the "out" movement of the speaker cone than it is on the "in" movement!

Let's try this same experiment on our PP amplifier. Each tube of the PP pair sees a signal that is in opposite phase to the other. In other words, when one signal is at the peak of it's positive half cycle, the other is at the peak of it's negative half-cycle. As a result, one power tube's plate current is rising while the other's is dropping, so that the two always average out to the same median combined plate current. To better illustrate this, we'll use integers and say that while at idle, both tubes are at zero. At the peaks of the signal cycle, one tube will be at say, +10, while the other is at -10, which averages to zero. Halfway through the cycle, one tube will be at +5 and the other at -5, which still averages out to zero. As a result, while one tube's Rp is dropping as current increases, the other's Rp increases as it's current drops.

Their Rp averages out to a median figure, and therefore the output Z also averages out to a median figure. This means (you guessed it!) the DF is steady as well, very much unlike our SE amplifier where the DF changed with each half-cycle of the input signal. This is what gives PP an inherit advantage in the bass department over SE, all other things remaining the same.

However, we used triodes in our test PP amplifier, and ran them in hard Class A. Triodes (especially low mu triodes) have far lower Rp than tetrodes and pentodes, and therefore will naturally yield a higher DF. But most PP amps use tetrodes or pentodes instead of triodes, which means very high output Z, a very poor DF, and almost non-existent bass. Why then do most PP amps have at least twice the DF of SE amps? The next section explains it all.

Negative Feedback

To further widen the sonic gap between SE and PP, consider that most PP amps use negative feedback (NFB), while *very* few SE amps use NFB nowadays. "Okay, that's nice" you say, "now, what *is* NFB?"

Negative feedback is a sample of the signal taken from the output of an amplifier stage and re-injected into the front of that same stage (local NFB), or into an earlier stage (global NFB), where it is 180° out of phase with the signal present at the re-injection point. In other words, "feeding back." Pretty crafty, eh? The circuitry contained between the two points is called the "feedback loop." Usually, the global feedback loop in a PP hi-fi amplifier will run from the speaker terminal back to the amp's input stage, thereby encompassing the entire amplifier circuit. Figure 6 points out the global feedback loop of a typical push pull amplifier schematic in bright red.

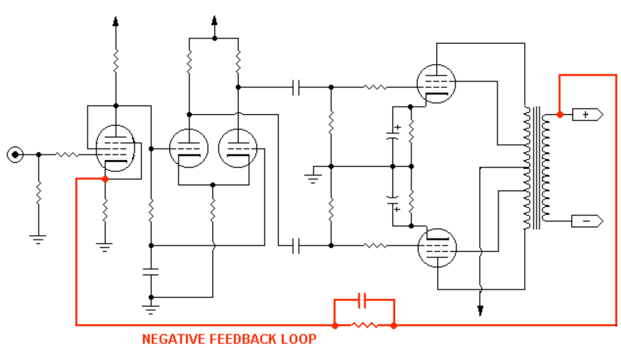

Fig 6 *Global negative feedback loop*

Your next question is probably, "Okay, now I know what it is. What does it do?" Good question. Well, it does a lot of good things.

(1) NFB reduces the distortion and noise in the stages contained inside the feedback loop. It cancels distortions in the same way our PP OPT cancelled power supply hum and second order harmonics earlier.

(2) NFB lowers the output impedance. This tightens and extends the bass.

(3) NFB flattens and extends the overall frequency response.

Most people at this point would be thinking, "Cool! Bring on the negative feedback!" Not so fast. NFB also does some bad things.

(1) NFB kills the space and air between the instruments, parts, and voices, rendering music dull and uninteresting.

(2) NFB reduces the stability of amplifier circuits

(3) NFB reduces gain.

Oh well...... Nothing's perfect, including NFB. *Especially* NFB. This first brings us to the early days of telephone service, where long distance telephone transmission lines were powered by tube amplifiers. Due to parasitic losses in the long, cross-country runs of wire, repeater amplifiers had to be used at intervals. The cumulative distortion of several of these repeater amplifiers was horrid, and telephone communications were difficult to understand as a result. NFB was invented at Bell Labs to lower this distortion, and it indeed worked very well. Without NFB, early long distance telephone communications across entire nations and continents would have been impossible.

Fast forward to the Golden Era of Hi-Fi, which was the original heyday of tube audio back in the 1950s and '60s, before mainstream solid state audio gear even existed. Just as it is in today's "big box store" world of mass consumer audio electronics, specs on paper meant everything back then. The lowest distortion at the highest power was what sold biggest. Lots of NFB was applied to everything, often even in multiple feedback loops. This was done because NFB lowers distortion, and to the uninformed masses the lowest distortion means the best sound. "Lower distortion *has* to sound better, doesn't it? I mean, distortion is a deviation from the original music signal, so lowest distortion means the most "perfect" sound, right?" No, it definitely *doesn't*. We saw this in the last section, "HARMONIC DISTORTION SERIES OF PP AND SE." The amp with the lowest distortion is not necessarily the best sounding. It more strongly depends on *which* orders of harmonic distortion are present, more so than *how much*. The human brain often disagrees with specs on paper as to what sounds best! Because NFB is taken from the very rear of the amp and injected back into the front, there is a frequencydependent time smearing effect that occurs, which the ear is extremely sensitive to. It blurs the focus and homogenizes the sound. The excessive amounts of NFB that was used to get the best distortion specs on paper was what made many of these amplifiers of yore sound lifeless and uninteresting to listen to, and is a major reason why today's big box store electronics sound so bad as well. Both may have ridiculously low distortion, yet there are amplifiers with literally a hundred times more distortion that sound better. Human psychoacoustics do *not* obey the laws of science very often!

So why do most PP amplifiers use NFB and most SE amplifiers don't? The main reasons are distortion and output impedance. Power triodes and triode-wired power tetrodes/pentodes were not used very much during the Golden Era of Hi-Fi, as a matter of fact almost never. Triodes produce comparatively less power than tetrodes/pentodes, and remember, specs on paper were everything so the most power won the day (or at least the sale!) Practically 99.9% of amplifiers used beam power tetrodes or power pentodes. As we saw in the last section, both of these tube types have very high plate resistance and therefore high output impedance. Neither is as linear as triodes; both types have much higher distortion. A zero feedback amplifier built using these types has high distortion, with much of it being the high/odd order type, plus the very high output impedance means the bass will be weak and flabby. It sounds bright, harsh, and thin, and literally unlistenable. So, NFB was a necessary evil with amplifiers using these tubes, both to lower distortion and yield an acceptable damping factor.

To make matters worse, many of these PP amplifiers had very complex, multi-stage signal paths to improve the specs on paper. This created more distortion, which of course required more NFB to correct! NFB reduces gain, so higher gain driver stages were needed to recoup the lost gain. Higher gain also means more distortion is created than in a lower gain scenario, which means (you guessed it) more NFB is needed to lower the distortion! It's like a dog chasing his tail, a vicious cycle to which there is no end, and nothing good can ever come from it. Plus, the immense complexity of such amplifers also degraded the sound, due to the sheer volume of components, solder joints, and jumper wires the signal had to travel through. Your music got ran through a huge network of sonically degrading components, and it sounded like it.

What's even sadder is that most of today's commercially produced PP amplifiers are still nothing more than tweaked-over copies of these same vintage circuits! Fact is, many (most?) of today's companies producing these PP amplifiers are still caught in this same "specs on paper" rut and can't seem to get out of it. I have this fancy saying about this, "Test equipment ain't got ears". The oscilloscope is not gonna be listening to it. The harmonic distortion analyzer is not gonna be listening to it. So who is? Humans! *We have ears and brains, not screens and displays*. As I had said earlier, psychoacoustics usually doesn't obey numbers written on a piece of paper.

Now that we've beaten the high feedback PP horse to death, let's move back to triodes and single ended operation. Triodes sound less bright, thin, and harsh when not using NFB, and have lower output impedance and lower distortion. A SE amplifier with a single, highly linear driver stage and a low plate resistance triode power tube can usually get by without NFB, which means the average SET amp is usually more open, airy, and purer sounding than an otherwise identical SEP (single ended pentode) amplifier using NFB to correct it's problems of high distortion and output impedance.

In Summary

We've seen that single ended and push pull amplifiers both have advantages and disadvantages. It's difficult to make blanket statements about each, as there are many variations of circuitry and quality in each broad category, so keep in mind these statements are generalizations. There *are* exceptions to the rule

ADVANTAGES OF SE OPERATION

- [x] Less signal deterioration because of fewer signal path components
- [x] Better detail and coherency, especially at low volumes
- [x] More open and airy sound

DISADVANTAGES OF SE OPERATION

- [ ] Poor efficiency, with low power and high heat production
- [ ] Almost no rejection of power supply hum and noise, which necessitates more power supply filtering
- [ ] No cancellation of second order harmonic distortion (some do not consider this a disadvantage)
- [ ] (Usually) shorter power tube life
- [ ] Has speaker compatibility issues, is less tolerant of wide impedance curves and complex crossover networks
- [ ] Poor damping factor

ADVANTAGES OF PP OPERATION

- ☑ More power
- ☑ (Usually) more authoritative and powerful sounding
- ☑ Better bass performance
- ☑ Fewer speaker compatibility issues
- ☑ Lower distortion

DISADVANTAGES OF PP OPERATION

- ☐ Homogenized, uninteresting sound
- ☐ More signal deterioration due to greater signal path complexity
- ☐ More power supply intermodulations between amplifier stages, and other power supply anomalies
- ☐ Poor low level detail and dynamics

Again, do note that these are generalizations. There are some horrible sounding SE amplifiers out there, and some very open and musical sounding PP amplifiers. It all depends on the design. If we apply SET design concepts to PP, using engineering practices aimed at achieving the best sound rather than the best specs on paper, the results can be astonishingly good. A PP amplifier using low Rp triode power tubes such as the 2A3 or 300B can get by with little or no NFB. For one, the triodes are an advantage in themselves, in both linearity and output impedance. Two, the front end voltage amplifer and phase inverter stages can be designed with much lower gain, if no NFB is present to reduce the available gain. Lower gain means lower distortion and lower output Z, so NFB is not necessary to attain these desirable properties. You end up with a much more linear amplifier, that has a simpler circuit with lower parts count and therefore less signal deterioration, and more air, breath, and vibrancy. See how much better everything gets when you set out to design it right from the beginning, instead of trying to fix it with NFB?

You're probably thinking, "There must be a catch." Well, there is. The power from such an amplifier is very low compared to high feedback PP amps using big pentodes. But, which would you rather have? 15 watts that sound scary good and leave you wanting more of the same, or 70 watts that bore you to death and leave you fatigued? Furthermore, in light of the huge number of highly efficient, great sounding speakers on the market today, amplifier wattage is a moot point. The pitfall to be avoided is not so much SE or PP as it is *high power*. By using very efficient speakers with minimalist or no crossovers, we can sidestep the whole power issue, and end up with much better sound, usually at lower cost as well.

High efficiency and low power is *the* way to go in this author's opinion. I grew up in a house full of vintage tube gear, and have owned both high and low powered tube and solid state gear. I've heard a lot of gear in my lifetime, and quite frankly, most of it isn't worth remembering. Most of what is put out well less than 10 watts. Nothing I've ever heard can compare to a good low powered tube amplifier with highly efficient speakers. SE or PP? Name your poison. Both have their place, and both can be fabulous *if* correctly designed and implemented. We can sum it all up in these words of wisdom, from one of the greatest tube amp transformer designers the world has ever known, Dutch electrical engineer Menno van der Veen:

"In reality, measurements are fine and can help you. But we have the finest measurement devices available on the two sides of our head: our EARS, and are not they fantastic? Well, use them and rely on them."

Eddie Vaughn