What’s the Buzz? – Part I

SJEP120R063A. DIY Audiophiles had their “religion” recognized by SemiSouth when the “A” was added to the part number.

The opening number in the play and movie *Jesus Christ Superstar* captures the excitement of a movement on the rise. Rumors, fantastic stories, sketchy details coming from that part of society on the outer fringes, both geographically and politically, create a sensation of something powerful in the offing. That judgment is confirmed centuries later with a most unlikely outcome: A world religion is born that subsumes one of the most celebrated empires in history. The SJEP120R100 is hardly in the same class of things to get excited about as Christianity, but I couldn’t help wonder when I first heard from the “Caesar” of SemiSouth (Jeff Casady) about the rapidly building interest within the audio community for the SemiSouth JFET: What’s the buzz?

While we’re on the subject of religion, I have a confession to make: I listen to music from an MP3 player through earbuds. There, I’ve said it. I’ve admitted my guilt. It wasn’t always that way. Some of my more vivid memories of youth are of either buying or getting access to what I considered upgrades to audio equipment. Back then, I made room for speakers, and used them to fill the room with music. I remember listening to the dynamic range on the *Can’t Buy a Thrill* compact disc by Steely Dan. Wow. I don’t remember a lot of things through a long life, but I remember *that*.

And then came the corruption. Frankly, when it comes to technology I’m an ancient adopter. That’s long after late adopter. Approaching never going to adopt, in fact. I remember reading an article in USAToday about a settlement Apple made on the batteries for the first iPod’s. Apple really assumed that people would throw away this personal audio gear in a year or two. Maybe they do now, but a few years ago, that was still a novel concept. An iPod was novel to me, I had never heard of an iPod until I read that article on an airplane. Soon, though, the thought of putting every item of music I currently owned, with room to spare for every item I might ever own, looked a whole lot like progress. It was a 20 GB iPod. Do you remember? The kind with a mini disk drive? Gosh that seems so ancient technology now (it’s sitting on my drawing table acting as a paper weight a couple of feet away from where I’m writing this). It might as well have been picked up in the ruins of the Forum. Flying on airplanes and driving in cars became the only time I listened to music. What a change from the days of my youth. Could listening to a song of my choice through a noise canceling headphone on a noisy airplane be worth this decline in audio quality? Maybe the day of my repentance is at hand. All I have to do is get Jim, my business partner and expert builder of electronics we concoct together, to finish the F2J. Come on Jim! I have some listening to do to catch up with the fine folks reading this. What *you* the reader may already know about a Nelson clone with a SemiSouth JFET I have yet to learn. I can’t wait!

What makes it sound like it does?

What could you learn from a sinner like me about why a SemiSouth JFET makes a fine sounding audio amplifier sound even finer? If we are talking about subjective measures, which are surely the most important because they involve the purpose of the whole affair, namely, listening to the audio reproduced, then you have nothing to learn from *me*. I've already admitted that I took a decade long detour into the wilderness of mass consumerism. So I promise that in this article there will not be even a hint of opinion about what makes it sound good to your ears. I hope to join you among the informed soon enough.

On the other hand, I have been a practicing engineer and an engineering educator for two decades. When it comes to the electrical measures of performance, sometimes called the "objective" metrics of an amplifier, my methods could add value; especially if we throw a SemiSouth JFET into the conversation. Of course you the reader will be the ultimate judge of that assertion, but assuming you are willing to invest a little time, let's get to it.

Zen Mod, anointed the "court jester" of the DIY Audio Forum by at least one poster (not me!), probably summed it up the best about what to look for among the objective measures: "we aren't chasing zeroes, but decent decimal and friendly THD harmonic spectra" (see the *SemiSouth Boiler Room* thread, post #134). From reading Nelson Pass' literature, and following the over-whelming thread of similar posts, it is clear this means considerably less than 1% THD at 1 W with the residual distortion being either second or third harmonic, depending upon one's tastes.

Since Zen Mod has instructed us to not think about zero distortion, we know we are dealing with an electronic circuit that is inherently non-linear. And the primary source of that non-linearity is the transistor, which is especially true for the types of non-magnetically-coupled Pass amplifiers we will consider here. That may not sound like much of a revelation, but I'm almost thankful that it is true because I know a few things about transistors. If non-linear transistors are our problem, isn't it logical to ask what a linear transistor is and do they exist?

Searching for the linear transistor–Transfer Curves

When I was an undergraduate taking my first college course in electronics, you would think that a linear transistor existed. Although the writer of this ancient introductory text book is well known in academia (I know his son, a NASA engineer, quite well), the problem was that the sophistication of engineering education needed to evolve. To be fair, back then we did not have near the computational tools at the fingertips of today's students (even though they resist using them!). It is true that by the time I went to engineering school slide rules were history, but the simple analysis I report in the box below entitled "You won't find a linear transistor here" would have been far more painful without an Excel spreadsheet running on my little netbook computer, which we certainly did not have back then. Now that I have taught the first course in electronic circuits more than once, I have noticed that modern text books have evolved decidedly to insisting on facing the hard truth: No real transistor is linear.

We can start with the transfer curve. As Nelson Pass in his incomparable "Sweet Spot" article (http://passlabs.com/articles/the-sweet-spot) points out, even the gold standard for active linear devices, the 300B electron tube, has non-linear transfer curves. The basic problem is that real active gain devices are electronic “valves” and thus have threshold conditions which must be met before they will conduct. That automatically and irretrievably eliminates the possibility of satisfying the strict mathematical definition of linearity: There can be no offsets from the origin. Even the equation of a straight line with non-zero y-intercept fails the mathematical test for linearity (a homework problem for a college math course). No transistor is going to do better than *that*. The curvature in the drain current near threshold is just an extra helping of non-linearity, because the device’s non-zero threshold voltage ended the quest before it got started. The box “You won’t find a linear transistor here” comparing transfer curves shows what a “linear” transistor’s transfer curve would have to look like. None of the transistor transfer curves match it. However, Class A biasing fixes the threshold non-linearity problem, and for that reason the audiophiles I’ve met on the Pass forum at DIYAudio.com are consistently pro Class A.

But ignoring the offset, the transfer curves appear to *approximate* a straight line at high enough drain current, where all of them start to look (superficially) like a linear transistor with transconductance of about 8 S. With that observation, modeling a real transistor’s transfer curve for its small-signal linearity appears worth discussing. Let’s end that quest before it gets too far from the pier. The transfer curves at higher current *appear* to approximate linear curves, but they really don’t by the standards of sub 1% THD sought by audiophiles or even regular people for that matter. Mr. Pass says as much in his article. I did trend analysis (a built in easy to use function of the Excel charting tool) on each curve in the box and came to three interesting conclusions:

1. At lower current, a real SJEP120R100 does not obey a square law, but a cubic law.
2. The widely available Pspice version of the SJEP120R100 mathematically models a square law.
3. A 2SC4004 *npn* transistor may become Ohmic at high enough current.

Let’s start with the first conclusion. This is a rather startling observation as it is not easy to find engineering literature that suggests a JFET will obey a cubic law (it’s there, look for practical discussions of cubic harmonic generation in RF mixers using JFETs). All three SJEP120R100 measured on my curve tracer showed transfer curves highly correlated with cubic polynomials. This observation may not be all that profound since most of my JFETs have transfer curves that fit well with cubic polynomials, which could be explained as a simple artifact of the mathematics of approximation. But more interesting is that the coefficients of these particular cubic polynomials can be approximately factored into the following equation:

$$I_D = K\left(V_{GS} - V_t\right)^3 \qquad (1)$$

where K is a constant of proportionality with units of A/V^3 and V_t is the threshold voltage. Could the cubic relationship indicate physics rather than just mathematics? Multiplying out equation (1) gives the full cubic polynomial:

$$I_D = K\left(V_{GS}^{\ 3} - 3\ V_t\ V_{GS}^{\ 2} + 3\ V_t^{\ 2}\ V_{GS} - V_t^{\ 3}\right). \qquad (2)$$

Trend line analysis in the Excel chart reports cubic polynomials with exactly the form of equation (2). This can be shown if we write the cubic polynomials printed on the chart in the following general form:

$$I_D = a_3 V_{GS}{}^3 - a_2 V_{GS}{}^2 + a_1 V_{GS} - a_0 , \qquad (3)$$

where the coefficients a_3, a_2, a_1, and a_0 are the numbers computed by Excel. By inspection of equations (2) and (3) it is easy to write

$$K = a_3 , \qquad (4a)$$

and

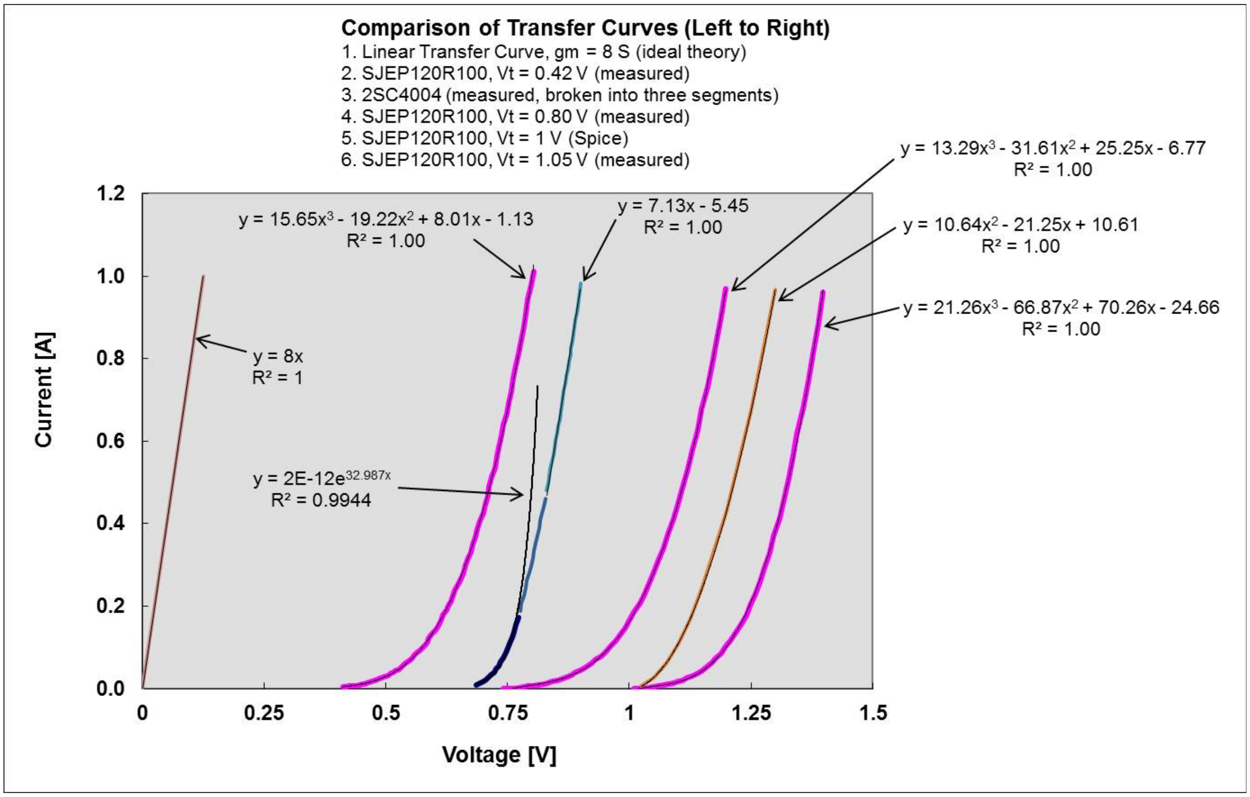
$$V_t = \sqrt[3]{a_0 / a_3} . \qquad (4b)$$

The table below shows the result of computing $3KV_t$ and $3KV_t^2$ after applying equations (4a) and (4b) to estimate V_t. The comparison of these computed values and the coefficients a_2 and a_1 from the trend analysis shows that, within reasonable error, the cubic polynomials from the trend analysis can be factored into equation (1). This is confirmed by directly factoring the polynomials which results in three roots clustered around the repeated root of equation (4b). My conclusion is that for these three parts equation (1) is a mathematical approximation that works well as a description of their *behavior* within this current range. I would not go so far as to suggest that this by itself is conclusive physical evidence that the SemiSouth JFET channel design is measurably different from the standard rectangular approximation found in text books, even though it is *not* rectangular by the way. But even if it were a rectangular JFET channel, first principal derivations do not give a theoretical square law for the JFET. An equation containing the 3/2 power is what you see in the text book. After the derivation, however, one text book reports that square laws are "empirically" observed with JFETs. Another, S.M. Sze's classic *Semiconductor Devices: Physics and Technology*, implies that observing square-law behavior in an enhancement-mode GaAs MESFET (a form of a junction FET) is an artifact of the design that allows the theoretical curve to be *approximated* by a square law through the mathematical method known as the Taylor series. Well, next up from the square law in a Taylor series is the cubic law.

Table I. Comparison of cubic polynomials from the trend analysis against a cubic-law.

SJEP120R100	$V_t = \sqrt[3]{a_0 / a_3}$	$3KV_t$	a_2	$3KV_t^2$	a_1
Very Low V_t	0.416 V	19.34	19.22	8.125	8.014
Low V_t	0.799 V	31.83	31.61	25.43	25.25
Typical V_t	1.051 V	67.00	66.87	70.42	70.26

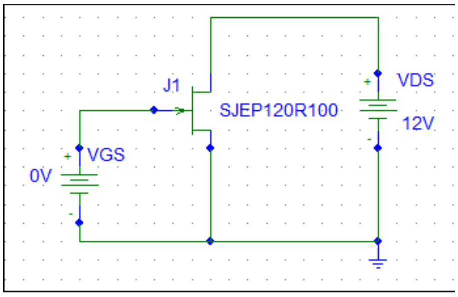
Another place to check for engineering data on this question is the widely available SJEP120R100 Spice model. Just put it into a Pspice software program of your choice and run DC Sweep analysis to compute the transfer curve. (See the box "Virtual curve tracer.") I did just



You won't find a linear transistor here. Inspection of real transfer curves, defined here as I_D versus V_{GS} at fixed drain-source voltage (or I_C versus V_{BE} at fixed collector-emitter voltage in the case of the 2SC4004 *npn* BJT), shows that no transistor can meet the strict definition of linearity represented by the y = 8x curve. This equation of a line with zero intercept is what a theoretical "linear" transistor with transconductance g_m = 8 S would look like. The SJEP120R100 trends to this relatively high transconductance only at the higher drain currents. The three SJEP120R100 transfer curves (pink lines) were measured from three different parts in my inventory and are the same ones shown in my first article (*Is it a SemiSouth?*, thread "SemiSouth Boiler Room," Post #2). A trend line analysis performed in the Excel Chart shows good correlation to a cubic law (R^2 = 1.00, where perfect correlation is R^2 = 1). In contrast, the Pspice model of this same part readily available on the DIY Audio forum reflects the standard square-law JFET model in Spice. As the drain current increases, the Pspice model and the measured data appear to converge to an effective square law, which is mathematically reasonable for small-signal analysis at a given operating point. The lone BJT transfer curve reveals an additional risk when using simple models to predict transistor performance in a circuit. This transistor has a 1 A "headline" rating, but as the collector current approaches 200 mA the transfer curve deviates from the exponential model (dark blue line) expected from the physics of an ideal BJT. I've extended the exponential trend line valid for I_C< 200 mA to show the departure from this trend by the actual data, which transitions (light blue line) to a rather straight curve (light green line). This reflects the reality that resistance internal to the transistor will limit the current at some point, and indeed trend line analysis prefers the equation of a straight line for this BJT as the current goes above 500 mA. In other words, ohmic current limiting will eventually take over the transfer curve in any real device if saturation does not occur first.

that and the result is included in the graph comparing transfer curves. That result correlates perfectly with a square law according to Excel trend analysis. No big surprise here. Providing Spice models to customers was a recurring headache for the company's sales staff, but it was never a high priority activity. What was done was done, and it built heavily upon the existing dogma that is represented in standard Spice models for JFETs and many other device types. There are two immediate observations to make about the transfer curve from the Pspice model versus the measured data. First, the definition of "threshold voltage" is clearly different, and the result is that the Pspice model is overly optimistic about the current that will be reached by a given gate-source voltage for real parts with the same nominal threshold voltage. That is obvious by comparing the real transfer curve of the SJEP120R100 with V_t = 1.05 V (as computed from the cubic law analysis) versus the Pspice model which has a V_t = 1 V built into its square law behavioral model. This mainly effects dc bias simulation, but no real harm is done because the threshold voltage of real parts is all over the place anyway. The Pspice model represents a caricature of a real part. Your part has only a low probability of acting like the model in the first place.

More troublesome is the question of predicting the ac performance of the transistor in an amplifier. The bottom line is what does it take to linearize whatever law you got? The shape of the transfer curve is pretty important to this analysis and even small variations from reality will produce big changes in the computed result for THD if the THD is expected to be low. But *that* problem is bigger than the transfer curve alone. In Part II we will explore a useful method for resolving this vexing problem of simulating faint residuals of non-linearity; and the best part is that it will be accurate for the parts in *your* inventory.



Virtual curve tracer. Pspice is a wonderful tool for testing amplifier ideas, especially since so-called "student" or "lite" versions of the Microsim-Orcad-Cadence variety are widely available as freeware on the internet. LTSpice is another option with a better transient solver, but it's missing some handy library tools like ABM models. But when using Spice, watch out! The validity of component models is something to question. I used the above schematic analyzed with a single DC sweep of VGS at a fixed VDS = 12 V to compute the transfer curve from the SJEP120R100 Spice model that follows:

```
.model SJEP120R100 njf
+ Vto=1 Beta=10.5 B=1
+ Lambda=2m Vk=2k Alpha=20u
+ Is=1f N=3.4
+ Isr=1n Nr=6.8
+ Cgd=1n Cgs=755p Pb=2.6 M=0.8
+ Kf=100f Af=1
+ VtoTC=-2m BetaTCe=-0.6 Xti=86
```

Searching for the linear transistor – Straightening the Curve

I'm reminded of that kitschy 1960's vintage television show, *Gilligan's Island*. (Alright, I thought it was 1970s too, but by that decade it was just re-runs.) A staple of the slap-stick humor in that show has the Skipper lecturing his "little buddy" that the absurd peril he is fretting about is impossible. During the lecture the peril (a gorilla or cannibal or ghost, etc.) is seen sneaking up behind him. Gilligan, who sees the impending disaster, tries to warn the Skipper. The Skipper invariably responds to the interruption by yelling, "Not NOW Gilligan!" Shouldn't *you* be pointing to my graph, as I discount the possibility of a linear transistor, to ask *me* what that sneaky 2SC4004 is doing acting like a linear transistor?

The observation of ohmic behavior in a semiconductor device with nominally non-ohmic physics is hardly novel. In fact it's commonly known in the power semiconductor industry. The device manufacturers set the headline current based on the rated thermal dissipation, and that is often met for a high-voltage bipolar junction device when the current is so high that the small parasitic resistances inside the device become significant. That is common enough for junction diodes; and perhaps it is true for this particular bipolar transistor, too. The necessary modification to account for internal "bulk" resistance R_b is found in Kenneth A. Kuhn's lecture *Diode Characteristics* (see www.kennethkuhn.com/students/ee351/diode_characteristics.pdf). But to apply this diode concept to a BJT assumes that the bulk resistance is in the base and the transistor current gain β is relatively constant, which in turn requires that the transistor be largely out of a high-injection effect called quasi-saturation. (High-voltage power BJT's are well studied, but complex.) Both assumptions are common approximations, and if we accept these assumptions we have a convenient equation that can fit our experimental data closely:

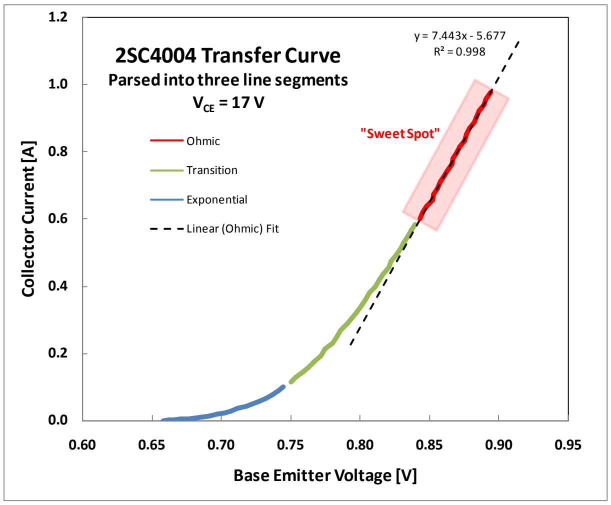
$$I_C = I_S \exp\left[q(V_{BE} - R_b I_C / \beta) / nkT\right], \tag{5}$$

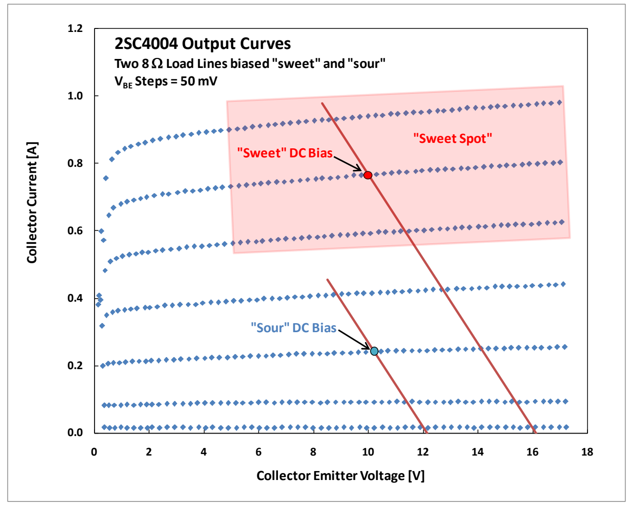
where R_b/β = constant. The general form of the solution to Eq. (5) is for I_C to initially follow an exponential curve that then gives way to a linear or ohmic curve at higher collector current. This is exactly what we see in our 2SC4004 transfer curve at collector-emitter potentials away from saturation. With Eq. (5) it is easy to apply standard small-signal theory to show that

$$\lim_{\frac{qI_C}{nkT}\frac{R_b}{\beta}\to\infty} i_c = \frac{v_{be}}{R_b / \beta}, \tag{6}$$

where I_C is the dc bias current of the BJT and i_c and v_{be} are small ac components of the collector current and the base-emitter voltage, respectively. Equation (6) is the very definition of an asymptotically "linear" transistor as the total loop gain given by the dimensionless ratio $qI_C R_b/nkT\beta$ becomes sufficiently large. But there is always the problem that we want power from our audio amplifiers and so when does "small signal" become large enough to see non-linear distortion in the actual output? We know *that* answer from Zen Mod's advice: There is no "zero" THD, meaning there is always some distortion and it will increase with the power to the load. The box "Electrokinesis!" takes a look at what we can expect from operating closer to the limit given in (6) which I call the *sweet spot* of this transistor.

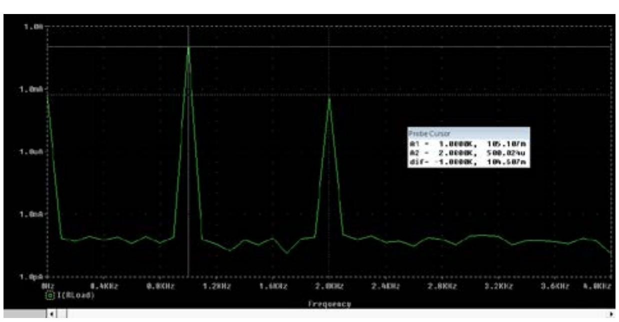
But how does that effect a discussion about the linearity of an amplifier using a SemiSouth JFET? The answer is that when we look at that exponential transfer curve "bending" into a straight line (or apparently a straight line) we are seeing the result of local negative feedback that is a close analogy to *internal* load-line cancelation. Think about it, what's the difference between a resistor internal to the transistor from a resistor external to the transistor if they are both in series with the junction? Perhaps at some detailed device physics level the internal ohmic resistance of the device might contribute greater feedback to the junction bias, but in principle, it's the same thing. Load-line cancelation of the transfer curve non-linearity requires the right



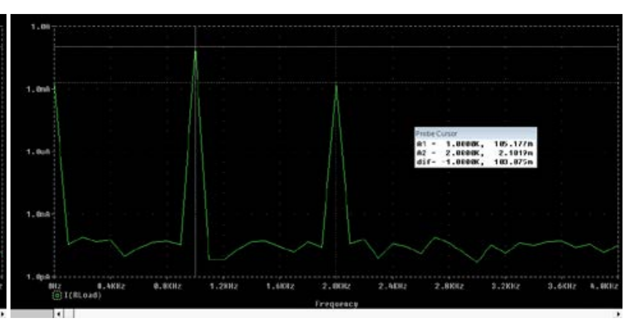


Electrokinesis! A fad when I was growing up was the claim of psychic energy sufficient to change the physical shape of common objects, like spoons. These claims of mind bending (debunked now) were called psychokinesis. But unbending non-linearity is alive and well in a Pass amplifier with a SemiSouth JFET as the gain device. One linearization mechanism is the change in the voltage across a resistor in series with the channel (FET) or junction (BJT) which is fedback to the voltage across the channel or the junction. The current is a function of both the gate-source (or base-emitter) voltage and the drain-source or (collector-emitter) voltage, which are in anti-phase to each other. This is load-line canceling and an interesting example of internal load-line canceling can be seen in the transfer curve of the 2SC4004 *npn* BJT above. The region above 0.6 A that shows an ohmic tendency is where we expect to find the “sweet spot” of this transistor as indicated on the curve. The output curves for this same transistor show the striking linearity of the spacing between the curves within the same collector current range as compared to the non-linear spacing at lower current. This region has also been marked as the sweet spot by a box. Finally, two examples of calculated Fourier spectra for an amplifier with 8-Ω load line are shown. One spectrum is for ac modulation about an operating point dead in the sweet spot, and the other spectrum is for ac modulation about an operating point below the sweet spot. The reduced THD from being in the sweet spot is remarkable.

Sweet: THD = 0.47%, Voltage Gain = 24.5 dB



Sour: THD =2.0%, Voltage Gain = 28.1 dB



shape in the drain current of the FET and a resistance in series with the drain, either in the dc or the ac equivalent circuit. This is what Nelson Pass tells us in his sweet spot article. The ohmic portion of the 2SC4004 transfer curve is a direct observation of the linearization effect caused by load-line canceling in the base that is reflected to the output curve by the proportional relationship between collector current and base current.

Despite the ohmic feature of the transfer curve, we can now drop the fiction of a linear transistor. We are no longer seeking the non-existent. We are instead trying to understand how to “bend” the non linearity of the transistor back into linear shape with the cooperative action of the amplifier the transistor operates in. The result is something far more than the sum of the parts: A substantially linear (but still imperfect) audio amplifier through load-line canceling.

If the transistor’s internal resistance can do the straightening for us, can’t the amplifier’s load (the speakers) hitch along for the ride? In principle, yes; but why we would want them to? One reason could be that a real speaker is not an ideal resistive load. But can we afford the cost in power dissipation? In addition to the other losses in the transistor inherent to Class A operation, we would be adding more dissipation in the internal resistance of the device. In other words, a fraction of the ac modulation created by the transistor that could be dissipated by the speaker is now being shared by the speaker and the transistor’s internal resistance. Of course, the transistor always incurs some loss in the finite drain resistance (i.e., the slope of the I_D vs. V_{DS} output curve), but for the unbending due to the internal resistance to be large enough to matter the loading from this internal resistance has to be quite substantial. I did an analysis of how much external resistance should be added to the dc path of the SJEP120R100 Spice model to make its transfer curve linear. I found that it could be done, but because this Spice model does not have nearly as much curvature in the output curves as a typical SJEP120R100, I needed to add tens of ohms and bias the amplifier to hundreds of volts to reduce the non-linearity to 0.1%. The cost in additional bias power was hundreds of watts. Not practical. Not necessary either, as this analysis was too pessimistic due to the flaws in the Spice model. The actual job can be largely done with the speaker impedance alone, which is the point Mr. Pass makes in his sweet spot article.

In Summary…

The bottom line is that the output curves of the SJEP120R100 have enough shape in the right direction to make the relatively small impedance of the speaker adequate to “bend” much of the non-linearity out of the transistor, which makes internal load-line cancelation exhibited by the 2SC4004 unnecessary. But load-line canceling is a process that depends upon many variables, some of which can be adjusted by you by playing with the bias settings, and others are hard coded into the parts themselves. And besides, load-line canceling is only one form of local negative feedback available to the designer. Other types of local negative feedback are evident in Pass amplifiers.

This article is the first part in a three-part series to examine the *buzz* about SemiSouth JFETs in audio. The principal topic was the transfer curve. In the next article, I’m going to look more closely at the output curves of the SemiSouth JFET and, in the process, give some suggestions for analyzing amplifier performance while accounting for the part-to-part variability in these curves. This is an aspect of simulation that Spice models handle rather poorly. In the last installment, I will ask where the final numbers for THD and residual harmonics come from in these amplifiers and in the process I will give negative feedback its due.

Happy listening!

Mike “Semisouthfan” Mazzola

If you have detailed comments about this article or you would like more information about obtaining SemiSouth JFETs, feel free to contact me at michael.mazzola@impowersystems.com. iMPOWER maintains inventory of SJEP120R100 and R100A, SJEP120R125 and R125A, SJEP170R550, SJEP120R063 and R063A, SJDP120R085, SJDP120R045, and other specialty SemiSouth JFETs. Transfer curve matching available upon request.

More reading…

http://passlabs.com/articles/the-sweet-spot