Second-order Harmonic Distortion Cancellation in the SE Amplifier :
Is it a sound practice?

by Ivan L. Johnston

…or is it distortion of distortion?

I've been struggling with this question since having first read about it in *Glass Audio* 4/96 (*Harmonic Cancellation Improves the SE Amplifier*).When I designed my PSE 845 Power Amplifier, I considered using second harmonic (H2) cancellation between the driver and output stages. Intuitively, increasing the distortion of any stage within an amplifier just did not sound like a good idea, and preliminary measurements during the prototyping of the first two stages confirmed my suspicions.

For those who are not aware of what I mean by H2 cancellation, I am referring to the practice of intentionally pre-distorting the signal at the driver stage, such that the second harmonic distortion that is produced by the output stage is canceled. You will find several articles in recent and not so recent issues of *Glass Audio*, touting the benefits of H2 cancellation (4/96: *Harmonic Cancellation Improves the SE Amplifier*, 5/96: *A 15W SE Amplifier With 6C33C-B* , 2/98: *A Pspiced Preamp With THD Cancellation*, 5/98: *Canceling Harmonics in SE Amplifiers*). The driver stage is typically either loaded down to increase the distortion, or the bias is intentionally mis-adjusted such that the H2 at the output of the amplifier is minimized. The distortion that is generated by the driver stage should most correctly be referred to as "complementary distortion",since it is simply the same form of distortion as that produced by the output stage, but out of phase. This should not be confused with inverse distortion, which is an entirely different subject.

Attempts to quantify the affects of H2 cancellation based on measurements made using real-world hardware have proven frustrating. It was easy to see what happens with a single test tone, but IMD tests indicated that there was what could best be described as a dirty noise floor over a large band of frequencies, which is difficult to quantify using traditional measurement techniques. Measurements are also limited by the dynamic range of the instrumentation, which for an HP3561A Signal Analyzer is about 80 dB. It has been suggested that distortion artifacts that are as much as 30 dB below the noise floor of an amplifier may have a significant influence on the perceived quality of sound produced by the amplifier.

In order to get a clear picture of what is going on beneath the noise floor, I decided to arithmetically model a simple two stage amplifier and analyze the results using various configurations for the driver stage. Rest assured, however, I will not be presenting a lot of complex equations involving high-order polynomials and Fourier analysis, the simulation model and the results are presented in a relatively easy to understand graphical form.

The model for each amplification stage is based on a polynomial. There are two coefficients in the polynomial that are adjusted as necessary to establish the desired amplitude of the H2 and H3 distortion products. Real triodes also generate higher order harmonics, but I do not think that this will invalidate the model or the results, since the higher order distortion products generated by triodes are typically very low. I considered using a higher order polynomial, but I could not find any published data showing the relative amplitudes of the higher order distortion products for the 300B. The noise floor is artificially created using a random number generator to produce Gaussian white noise. The same seed value is used for the noise generator in each of the simulations, so the background noise floor is identical in each case. Each amplification stage provides unity gain, so this eliminates errors that could be attributed to different amounts of gain in successive stages. All in all, I consider this to be an optimum environment for exploring the potential of each system topology.

Figure 1 illustrates block diagrams of the two models that were analyzed, the Two-stage Amp With a Linear Driver and the Two-stage Amp Utilizing H2 Cancellation. The output stage is exactly the same in each model. The output stage models the characteristics of a 300B operated with 350V from plate to cathode, 60mA of standing current, and a 3K Ohm load impedance. This is your typical 8W 300B output stage. The distortion values
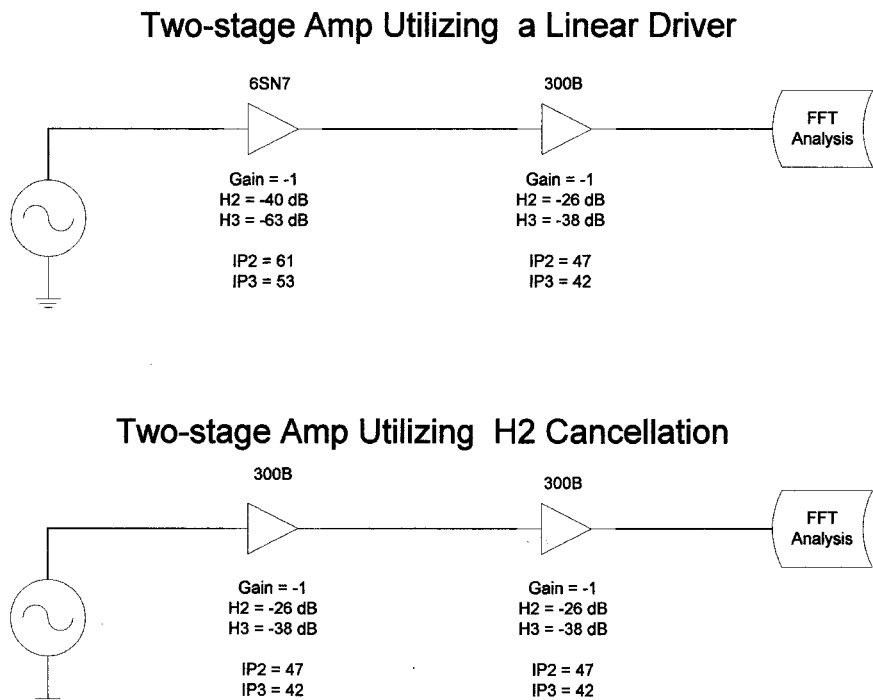
Two-stage Amp Utilizing a Linear Driver

6SN7	300B
Gain = -1	Gain = -1
H2 = -40 dB	H2 = -26 dB
H3 = -63 dB	H3 = -38 dB
IP2 = 61	IP2 = 47
IP3 = 53	IP3 = 42

Two-stage Amp Utilizing H2 Cancellation

300B	300B
Gain = -1	Gain = -1
H2 = -26 dB	H2 = -26 dB
H3 = -38 dB	H3 = -38 dB
IP2 = 47	IP2 = 47
IP3 = 42	IP3 = 42

Figure 1—Block diagrams of models under analysis

Figure 2—300B, one tone sinusoidal input

Figure 3—6SN7 driver, one tone sinusoidal input

Figure 4—Two-stage amp, linear driver

(H2=−26dB and H3=−38dB) and operating points were taken directly from the Western Electric data sheets. Figure 2 illustrates the response of this stage, with a sinusoidal test signal applied to the input.

The driver stage for the first model simulates the characteristics of the 6SN7 used with transformer coupling and a cathode resistor bypass capacitor. The distortion figures for this stage (H2=−40dB, H3=−63dB) were taken from Lynn Olson's excellent article that appeared in *Glass Audio 4/97* (*Sound of the Machine: The Hidden Harmonics Behind THD*), and represents the distortion of the driver stage at 50Vrms, which is just sufficient to drive the 300B output stage to full power. Figure 3 illustrates the distortion characteristics of this driver stage, again with a sinusoidal test signal applied to the input.

The driver stage for the second model, the model utilizing H2 Cancellation, utilizes the 300B model for both the driver and the output stage. This is representative of using a 300B to drive a 300B, with direct coupling and the exact same load impedance for both stages, the theoretical optimum application of complementary distortion.

The plots of the results were made by performing an 4096-point Fast-Fourier Transform (FFT) on the output of each model. I used a Hanning function to compensate for the bin spreading that results from the finite number of samples that are processed by the FFT, so the results are quite accurate. These plots are analogous to what you would see on a spectrum analyzer. The x-axis represents frequency relative to the sample rate, which in this case is 100kHz, so the x-axis value of 0.1 corresponds to 10 kHz. The y-axis represents the amplitude on a logarithmic scale, so the measurements are in decibels (dB) relative to an arbitrary reference.

Let us first examine what happens when a single tone is processed through these two different amplifier models. Figure 4 illustrates the spectrum of the output of the first amplifier model, with the linear driver stage, reproducing a single test tone. Notice that there are distortion products extending to the seventh harmonic. How can this be, the model of each amplifier stage only produces H2 and H3? The answer is simple, the H2 and H3 produced by the driver stage are turned into H4 and H6 in the output stage, and the H5 and H7 are intermodulation distortion (IMD) products. These higher order distortion products are literally "distortion of distortion." Figure 5 illustrates the
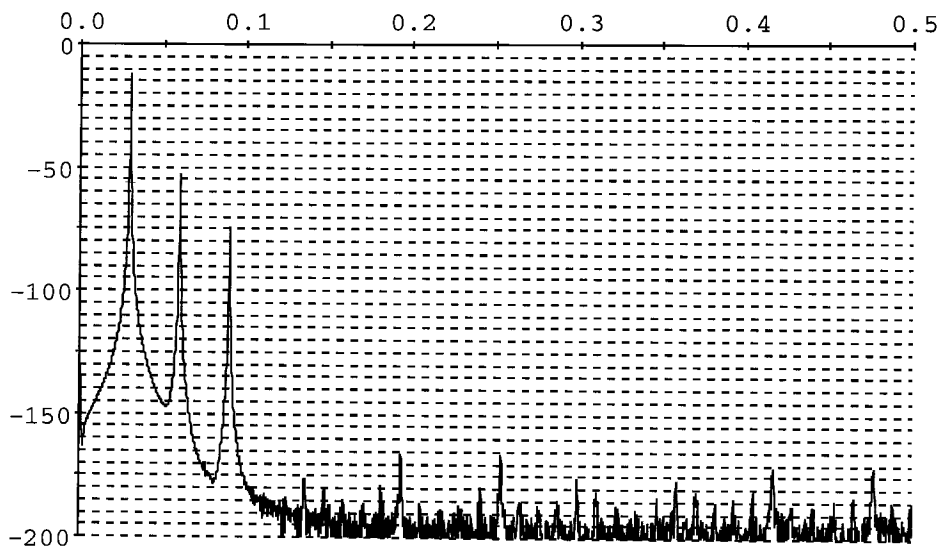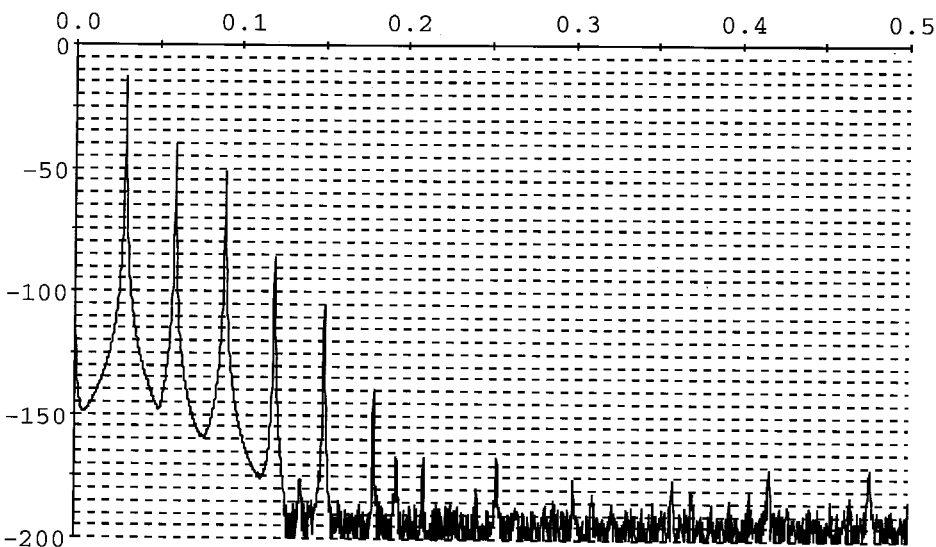
output of the model using the non-linear driver stage. As expected, you can see that the H2 level has been reduced approximately 25 dB. There is a price for this reduction in H2, however, note the large increase in the higher order harmonics. The H3 has been increased by 6 dB (6 dB is a doubling of the distortion!), the H4 has increased by 6 dB, the H5 has increased by 22 dB, the H6 has been increased by 34 dB, and the H7 has been increased by 42 dB.

Figure 6 and Figure 7 illustrate the results for the two models when simulating a two-tone intermodulation distortion test.Notice how the IMD products rapidly fall-off for the model using the linear driver stage. Close examination of the IMD products from the model using the non-linear driver stage, Figure 7, shows that there is suppression of some of the IMD products that are close-in,but again there are now IMD products that extend much higher in frequency.

Conclusion

I believe that Chapter 14 of the *Radiotron Designers Handbook* should be required reading for everyone involved in audio amplifier design. Langford-Smith discusses some studies performed by Olson and Shorter, in which it was found that the higher order harmonic distortion products should be weighted, in order to make these measurements correlate with subjective listening tests. Olson's study suggested a weighting factor in which the measurements for each harmonic should be multiplied by the harmonic number, while Shorter's results suggested that the measurements should be multiplied by the square of the weighting factor!

Clearly there is a price for the reduction in H2 that the cancellation technique provides. The third and higher order harmonic distortion products that are generated by the driver are additive to the third and higher order distortion products that are generated by the output stage. By directly additive, I mean that the percentage of each harmonic at the output of the amplifier (excluding the H2 component) is approximately the peak sum of the distortion produced by the driver and output stages, not the RMS sum.The THD (the sum of all the harmonics taken as a whole) is always the RMS value of all the harmonics, which is why you end up with a lower THD measurement when you cancel out the large H2 component.The IMD test results are more difficult to interpret,but it is fair to say that there are more IMD products generated when using the non-linear driver stage,
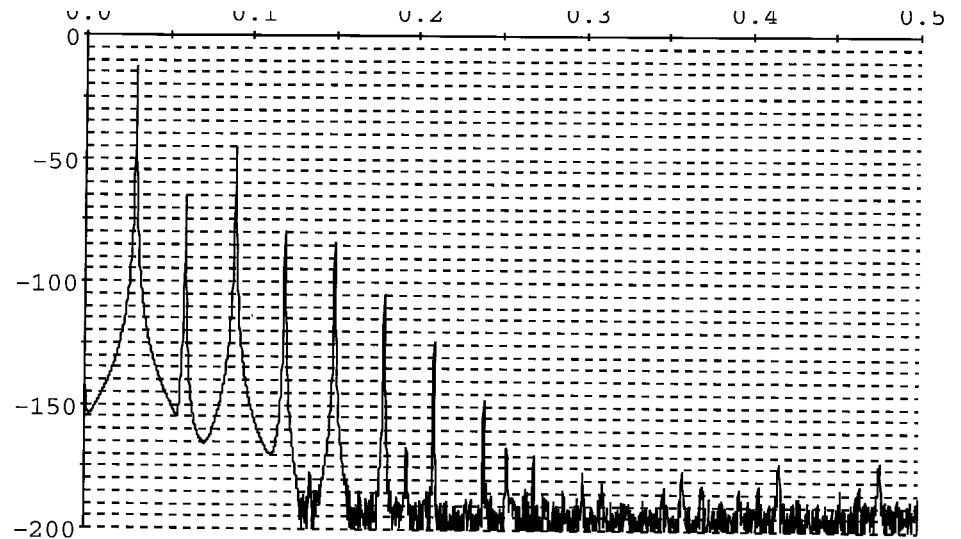

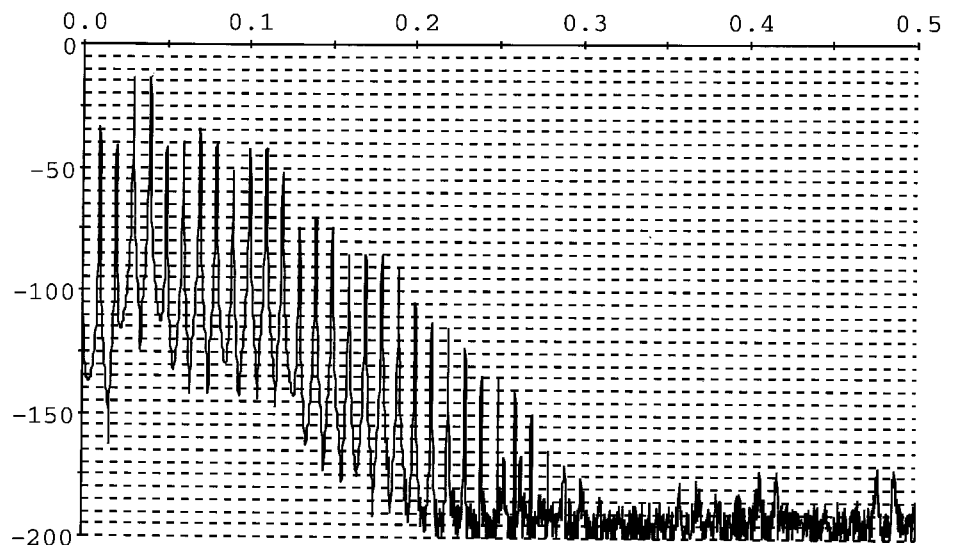Figure 5—T wo-sta ge amp , non-linear driver

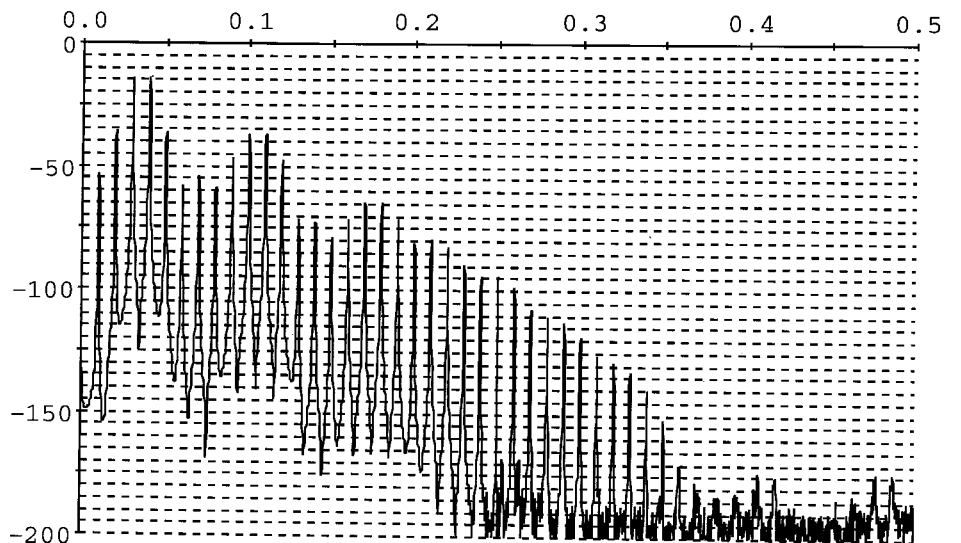Figure 6—T wo-sta ge amp , linear driver , two tone test

Figure 7—T wo sta ge amp , non linear driver , two tone test

although there is a reduction in the amplitude for many of the close-in IMD products. To some extent, the IMD products are spread out over a larger frequency band when the non-linear driver stage is used.

Ultimately, each of us must choose what sounds best, as that is the bottom line. I have experimented with H2 cancellation using my own hardware, using test equipment to setup the driver stage with enough distortion to cancel the H2 at the output of the amp. It is very satisfying to achieve extremely low THD measurements with a single-ended design without using negative feedback, but are we measuring the right thing? After critical listening, I have concluded that for my ears, in the context of my system, a linear driver stage sounds better, despite the higher measured THD. I find that the difference is most notable when reproducing piano music and female vocalists. With a linear driver stage, the notes of the piano smoothly decay into a black background. When the highly non-linear driver stage is used, there is an edge of graininess that is clearly audible as the piano notes decay. There seems to be less space between the individual notes. The sound of some female vocalists can change significantly, to

me there seems to be an edge added to some voices when the non-linear driver stage is used. Do not take my word for this, listen for yourself. I have always subscribed to the theory that SE amplifiers sound good in spite of the high levels of low order distortion, not because of them. This leads me to conclude that the reason they sound so good is the relative absence of high order distortion products. If this premise is wrong, if SE amplifiers sound good because of high levels of euphonic H2 distortion, it could be that the change for the worse is the result of the reduction in H2, and not the increase in the higher order distortion products. Since the reduction in H2 is accompanied by an increase in the higher order distortion products when the H2 cancellation technique is utilized, it is impossible to isolate the effects.

The popularity of the single-ended triode amplifier, without negative feedback, is in my opinion largely due to the fact that there is no substitute for linearity at the device level. The concept is simple, build the amplifier using the most linear devices available, and use those devices in circuits that extract the full potential of those devices, eliminating the need for negative feedback.

The current trend of using distortion cancellation, intentionally increasing the distortion at the driver stage, is very disturbing. In my opinion, those who are touting the benefits of distortion cancellation in SE amplifiers have gone full-circle. They have resorted to techniques that result in low THD measurements, for specsmanship, at the expense of musicality.

About the Author :

Ivan has over 20 years of experience working with electronics. He is presently a Senior Engineer at Interstate Electronics Corporation, Anaheim CA, where he designs signal processing hardware and software that is used in military Global Positioning System (GPS) satellite receivers, and missile tracking systems. In his spare time, Ivan designs and hand-crafts custom preamplifiers and power amplifiers, and he regularly gets out to listen to live jazz at various venues in Southern California. You may contact Ivan at the following address:

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