Audio Expert Reminisces

An esteemed engineer, electronics authority, and prolific author talks audio

SHANNON BECKER: Where are you located?

WALT JUNG: My wife Anne and I live in a rural location on the United States's east coast, complete with an acoustically treated POOGE room, basement lab, home office, and many (sometimes functional) computers. Our two children live within short distances, with our five grandchildren.

SHANNON: How did you first become interested in electronics?

WALT: Way back in my teen years, I had the good fortune to have a kind uncle and tech-savvy mentor, Harry Miller. He first exposed me to the vacuum tube electronics of that time, the mid-1950s. This was the golden era of Elvis, Jerry Lee Lewis, and those fantastic-sounding Mercury mono classical LPs. In my quest to explore and absorb this new domain, I read everything I could find about electronics in general, and particularly amplifier circuits, devouring magazines such as *Radio-TV News*, *Audio*, and others.

I began building things after tearing down many old radios, gifts courtesy of a generous local TV repairman. I fixed and restored some of them. Others went into my part bins, or became platforms with new audio lives. They were all good learning experiences!

I also built many Heathkits, as well as Eico, Arkay, Dyna, and others (see **Photo 1**). These kits were both Hi-Fi and more general-purpose, and each was a labor of love (see: "Those Long-Lost Hi-Fi Kits," *The Audiophile Voice*, Vol. 10, #4, 2005). I also scratch-built my own Williamson power amp, which matched up with a Heath WA-P2 preamp as my mono system nucleus—a pretty neat trick for a 15-year-old kid. Later, I added an extracurricular low-power AM radio venture to talk to high-school classmates. I never lost the keen taste for kit building, and later on did numerous *Audio Amateur* "Kit Reports."

SHANNON: What appeals to you about analog electronics in particular?

WALT: To me, the analog world represents a real electronics world, processing signals that are "sound, music" analogs. With audio, it is also the most challenging, as dynamic ranges can be 100 dB or more, and signals must be handled carefully to avoid distortions detracting from the original. Here, everything does matter.

SHANNON: When did you first write *IC Op-Amp Cookbook*? What was your motivation? Tell us about the process.

WALT: *IC Op-Amp Cookbook* was first published in 1974 by Howard W. Sams. Today, nearly 40 years later, it is still in print as a 3rd edition, which is almost unprecedented for a technical book. The making of it actually took a couple of years. It was done working part-time, with two leaves-of-absence from my day job, and in between challenges of Sunday-league softball.

By the early 1970s I'd been prepping the magazine work toward a book, and had written many applications articles on op-amps and other integrated circuits (ICs). This included "The Pitfalls of the General-Purpose IC Operational Amplifier as Applied to Audio Signal Processing," in the November, 1973 *Journal of Audio Engineering Society*.

The very first edition of the *Cookbook* was large (591 pages!), so a couple of chapters were spun off as standalone books, one being *Audio IC Op-Amp Applications*, which went through three editions.

The motivation for *IC Op-Amp Cookbook*, as well as for the other Howard W. Sams books I authored, was this: In user-friendly terms, describe how to effectively use analog ICs, then relatively new. Ultimately, this led to 10 Sams books, with the most popular ones *IC Op-Amp Cookbook*, *Audio IC Op-Amp Applications*, and the two editions of *IC Timer Cookbook*.

Photo 1: A youthful Walt Jung at the Hi-Fi and radio shack controls, late 1950s. Note the Heathkits WA-P2 pre-amp and FM-3 tuner (middle shelf), plus the home-built power amp (bottom), and magazine stack (right).

SHANNON: For readers unfamiliar with the book, what is it about? What will they learn?

WALT: *IC Op-Amp Cookbook* (any edition) is all about cutting through abstract academic depictions of IC op-amp operation and presenting clear, practical circuits that to do useful analog things. This, of course, is a lot broader than just audio, and it includes other standard applications. The *Cookbook* uses real part numbers and has real circuit values, and so forth. If you aren't into circuit building, it likely won't be of great interest. Of course, over 40 years of time, many earlier part numbers have gone obsolete. Yet, basic principles of operation still apply. If one is looking for audio operation of op-amps, *Audio IC Op-Amp Applications*, 3rd edition is a good choice.

Both books can be found at Abe Books (www.abebooks.com).

Much more recently, I edited (and authored sections of) another op-amp book, as an employee of Analog Devices, Inc. (ADI). This one, *Op Amp Applications*, is nearly 1,000 pages, and was published in 2002, just before I retired from ADI. Chuck Hansen, an *audioXpress* contributor, reviewed it in April 2004, and I thank him for his many kind words. This book is also available as a free download (www.analog.com/library/analogDialogue/archives/39-05/op_amp_applications_handbook.html). Another version can also be purchased from Newnes, as *Op Amp Applications Handbook*.

Photo 2: The Sound Technology 1700B test set was used for IC op-amp testing in the 1970s.

SHANNON: In 1977, you wrote a series of articles on slewing induced distortion (SID) in audio amplifiers for *The Audio Amateur*. How do you think SID and transient intermodulation distortion (TIM) are treated (or not) in modern amplifiers?

WALT: Yes, that 1977 series was big for Ed Dell, *The Audio Amateur*, and also me. It was expanded into an 1977 Audio Engineering Society paper, and another adaptation appeared within *Audio* magazine in 1979. These papers can be found on my website (waltsblog.waltjung.org). While the AES didn't choose to publish the paper in the *Journal*, they did see fit to award me a 1979 fellowship, "for his publications on the subjects of audio applications of integrated circuit operational amplifiers and the analysis of distortion."

This IC testing was updated into a standardized series, within *Audio IC Op Amp Applications*, 2nd and 3rd editions, Sams, 1978 and 1987. It is hard to imagine, but all those many swept-frequency THD+N tests were manually plotted, using a Sound Technology 1700B test set (see **Photo 2**). More recently, Samuel Groner has updated this methodology, and enhanced it with additional tests. His website has test data for many IC and modular op-amps (www.sg-acoustics.ch/analogue_audio/ic_opamps/index.html).

So, it may be true that this work had useful amplifier design influences. But I'd also qualify that, as there were many others writing on SID/TIM. For example, the late Marshall Leach, along with John Curl and Bob Cordell, to name a few.

SHANNON: Matti Otala was the "inventor" of TIM, and you defended his findings at the time. With the benefit of hindsight, how do you view it now?

WALT: I look upon Matti Otala's work as an examination of amplifier large-signal dynamics by means of its transient behavior, TIM. What I found in my testing was that much of this could also be explored by conventional swept-frequency/level THD+N measurements. And, if an amplifier had a sufficiently high slew rate (SR), it would likely also have low measured THD+N, as well as no (or low) TIM. This is a simplification, aimed to fit the context of this limited discussion, and doesn't account for other possible dynamic anomalies.

However, there is a potential controversial point associated with TIM and op-amp behavior. Most op-amps usually have high open loop (OL) gains, and typical OL bandwidths well below the 20-kHz audio range. In closed-loop (CL) operation, the effective bandwidth is widened via feedback, resulting in a larger CL bandwidth. But, the feedback loop dynamics will dictate that the amplifier error signal will vary in amplitude with frequency changes, for a steady amplitude output. Or, for fast edge, high amplitude transient signals, the error signals have their greatest amplitude. This is a central point of TIM, which occurs in cases where the error signal reaches a point of input stage overload (i.e., hard TIM).

This dynamic overload is prevented by designing the amplifier input stage so that it linearly accommodates the largest amplitude input signal ever expected. Under such conditions, the amplifier always remains in small signal operation (i.e., below its SR limit) and no (hard) TIM occurs.

There are also more subtle distinctions to be acknowledged here. An amplifier might have a sufficiently high SR to prevent hard overload, but still have an OL bandwidth less than 20 kHz. Most general-purpose op-amps, even those designed for audio, don't have high OL bandwidths, so this situation is difficult to avoid. In fact, I can only think of a couple of devices with OL bandwidths approaching 20 kHz. One is the AD825, with a gain of 66 dB. But, one can create multiple-loop topologies with standard devices, with an effective OL BW of greater than or equal to 20 kHz. Examples of this are on my website (see Walt's Tools and Tip columns on audio).

There is also an option of local feedback to the op-amp, essentially operating it in a *transconductance mode*. This interesting option was discussed way back in a 1980 AES convention paper (also available on my website).

SHANNON: You are considered a DIY audio guru. Paul Hutchinson, an embedded systems designer, referred to you on his blog as "one of the greatest engineers of all time." Looking back on your career, is there anything you would do differently?

WALT: First, let me say that I find Paul Hutchinson's assessment most flattering, and thank him for it. Upon receiving this question, I reached out to thank him, and he reported recently using both *IC-Op Amp Cookbook* and LTspice, to verify a recent design. I find it gratifying that he could do so—as the *Cookbook* never met SPICE!

I suggested to him that perhaps one strength of the book lies in the ability to endure, even after almost 40 years. He replied, saying "Yes, boiling down my roundabout writing style, *IC Op-Amp Cookbook* has definitely stood the test of time." Thanks again, Paul!

As for what I would do differently career-wise, that's a tough one. I'd say, not a whole lot—maybe retire a bit earlier!

SHANNON: You have had a long and distinguished career. You were an apps engineer at ADI for 11 years, before retiring in 2002. Before that you worked at Linear Technology for a few years, reporting to co-founder Bob Dobkin. You also consulted to both ADI and Precision Monolithics before their merger. Could you discuss what you consider some of the highlights of your career?

WALT: The opportunity to work for companies such as LTC and ADI I do consider major highlights. Lots of app notes and seminars! With ADI, I got a chance to revisit op-amp applications again in a book, and unearthed loads of historical background. Of course, all of the various books, and the op-amp distortion work were also great satisfactions.

Here, I should also point out that my career was aided in several instances by people who provided me with key opportunities. This would include magazine editors Ed Dell (former *Audio Amateur* editor/publisher) who proved a platform for so many DIY and other articles; Ron Merrell, former editor of *Broadcast Engineering*, who generously provided space in *BE* and also introduced me to Howard W. Sams; Gene Pitts, former editor of *Audio*, who ran many key articles of mine; and the late Bob Milne, my column editor at *Electronic Design*. And, a most helpful early engineering contact was Bob Dobkin, then of National Semiconductor, who provided me with access to NSC literature for use within *IC Op-Amp Cookbook*. Much later, he became my boss at LTC. I am most thankful for all these key individuals for their encouragement at critical points.

SHANNON: You have written numerous articles for *Electronic Design* (*ED*) and many other publications over a 40-year period beginning in late 1960s. Of particular note is a column you wrote for *ED* called "Walt's Tools and Tips." What are some of the most memorable tips and are there any that are no longer applicable due to changing technology?

WALT: Yes, the run with *ED* was longer than with any other magazine. And, the *ED* "Tools and Tips" gig, plus the long association over so many years were highly rewarding career experiences. As was my 2002 inclusion into *ED*'s "Hall of Fame." My editor for "Tools and Tips," the late Bob Milne, contributed significantly to its success, making it both a real pleasure and career highlight. All of those columns are reprised on my website.

As for tips not making the grade of

time due to evolution, yes, some fall in that category (readers can see for themselves). But of all the columns, the last four on op-amp audio have been very popular and are still well recommended.

SHANNON: Tell us about your website and how it came to be.

WALT: There are actually two sites—the older site (www.waltjung.org) and the blog site (waltsblog.waltjung.org). The original intent was to archive some of my articles written over the years. The more recent blog is intended for interactive use, as well as providing (free) access to more recent publications.

SHANNON: At one time, you posted quite frequently on various audio websites. Do you still frequent any audio forums?

WALT: I have cut back on online activities, but not altogether. It takes gobs of time to run a website, but alas, family is a priority—gotta keep the grandkids happy!

Despite such caveats, I have posted some findings in an area of great personal fascination, current sources within audio applications. Specifically, the "Baxandall Super Pair" forum thread on the *DIY Audio* website is involved with a unique combination of complementary bipolar transistors, having high output impedance (www.diyaudio.com/forums/solid-state/25172-baxandall-super-pair.html). The U.K.'s Baxandall and Swallow namesake work was dated in 1966. But there was related work predating it, and other U.S. and U.K. work, afterward. All in all, a fascinating study of 21 high-performance current source papers can be found in the bibliography. It was fun working with fellow audiophiles Dimitri Danyuk, Samuel Groner, and Brad Wood on this project.

SHANNON: Do you think progress has been made in audio op-amps since the mid-1990s? If so, what kind of progress? Do you have any specific recommendations as to which modern op-amps are best for high-quality audio?

WALT: How far have we come with ICs for audio? I'm reminded here of the late Bob Widlar's response to a query, at a 1970's IEEE ISSC conference, when I first met him, as well as John Curl. Curl asked Widlar about using his op-amps for audio. The response went something like this: "Handling audio? We never designed these amplifiers for processing audio!" As Curl pointed out to me recently, this true story is an honest Widlar statement on using his IC's for audio. According to him, they weren't designed for the purpose, so we should make our own. Of course, it's appropriate to point out that Curl has had good success in doing just that. Widlar went on to make major industry contributions to op-amp designs, but not many were known for high speed. Another gifted National Semiconductor designer, Bob Dobkin, designed a fast and linear op-amp in 1971, the LM318—sufficiently linear in terms of SID effects such that it was used as a reference amplifier in my 1977 test series.

There has been great progress in IC op-amps more recently. This can be discerned by comparing devices from *Audio IC Op Amp Applications*, 3rd edition, and those within Chapter 6 of *Op Amp Applications*. Or, by reviewing leading IC source datasheets. Modern devices built on fast, complementary processes enable higher speeds, and more linear, higher current outputs. For the input, FETs have improved over older devices (e.g., TL07x series). Noise has been lowered dramatically, with several bipolar devices capable of sub-nV/√Hz voltage noise, (e.g., the LT1028 and the AD797).

But, in fairness, the best performance available with selected discrete devices (FET or bipolar) will most likely make IC performance lag behind, due to process restrictions of the latter. This becomes a tradeoff issue. If you choose to go all out for performance, you will then end up with more parts per stage. On the other hand, with a carefully chosen and applied IC op-amp, you can end up with a single IC and just two resistors for a stage, at a modest cost. It is your choice here.

As for specific part numbers, I'd hesitate to name any single part for universal use. The best IC op-amp will always be the one that best matches the application requirement. I would suggest here that interested readers download the latest test information from Samuel Groner's website (as noted), for a broad-based current perspective.

SHANNON: In 1995, you wrote, with contributions from Jan Didden, a series of landmark articles on the power supply regulator in *The Audio Amateur*. Do you feel progress has been made in the years since, and what is the most important spec for a regulated audio power supply?

WALT: Yes, that was another notable series of four parts. I did the first two parts, on theory of operation and testing, while Didden did part three, on a PCB for the project. Gary Galo also made major contributions in part four, on building and installing, plus listening tests. Much later on, this regulator topology was updated, in "Improved Positive/Negative Regulators," *Audio Electronics*, Issue 4, 2000. (waltjung.org/PDFs/Improved_PN_Regs.pdf). One key feature of the new design was the operation of the regulator stage itself in a bootstrapped fashion (i.e., the regulator regulates its own output, or in a two-terminal mode). I will provide more on these two items, below.

In *audioXpress*, November and December 2009, Didden interviewed Malcom Hawksford on various audio topics. Within part one, Hawksford made a valuable point related to power supplies, which is that *a shunt-type regulator localizes audio dynamic currents*. Going further on this theme, in contrast, a series-type regulator returns dynamic audio currents all the way back to the raw DC supply! The latter type uses a long-series loop, as opposed to the short loop of a shunt. For audio, there are some profound implications to these differences.

Now, we all know that *all* series circuits (by their nature) *carry the same current at all points along the loop*, both in the hot and ground legs. So, with a series regulator, the output signal current from an op-amp or other single-ended active stage—*it doesn't matter whether it is tube, transistor, or whatever*—will flow back through the regulator, and the raw-supply rectifiers. Or, if there is no regulator used, the audio currents still flow back through the raw supply.

The point here is simply that there is potential for distortion problems in such cases, as the extremely nonlinear AC rectifiers and filter caps must carry the audio signal. *Given the above perspective, there can be no doubt that the signal path of an audio system using single-ended amplifier stage(s) includes the raw power supply in the current flow loop, to some degree.* In all fairness, it should be noted that a practical series-type regulator audio application isn't likely be a pure series circuit loop, as drawn on paper. Why? Typically, AC bypass caps are used before or after the regulator. This helps mitigate the situation, as it can reduce the dynamic audio currents flowing through the raw DC supply. Reduce, but not eliminate entirely.

In stark contrast (any) shunt-type regulator provides inherent isolation between the audio stages and a dirty raw supply, by virtue of a high-z series input leg consisting of either a current source (or a choke), and a shunt regulator stage that regulates its own terminal voltage. In this manner, all audio signal currents are confined to the short loop formed between the regulator and audio stage and they never mix with the raw-supply AC currents. A good shunt regulator will use a current source with many megohms of impedance, and a very low capacitance, minimizing potential noise coupling from the raw DC supply. The DN2540 MOSFET cascode pair is a excellent choice here, in fact this was a design goal of that circuit (see waltjung.org/PDFs/Sources_101_Letter_Revisit_0409.pdf).

For the regulator proper, *it must by necessity be able to operate in a two-terminal mode*, as noted. This is fortuitous thing, as it turns out the main ingredients for a good shunt regulator are contained in the very same regulators as described above, the "Improved Positive/Negative Regulators!" No preregulator stage need be used, as this function is replaced by the cascode DN2540 current source. The original pass device of the series "Improved Regulator" is replaced by a complementary shunt device. For example, the original positive-series regulator uses an NPN pass device. To operate it in a shunt mode, a PNP device is used, with the collector tied to common.

The point I'm leading to is that an existing set of PCBs that supported the topology of "Improved Positive/Negative Regulators" can, with minor changes, also be operated as a shunt-type regulator. An example is shown in **Figure 1**.

The key is that the two-terminal regulation topology of this design enables for it. But, this is after some minor changes: the level shift diode D8 is set to a voltage close to one half the desired output voltage (6.8 V); the deletion of the on-card NPN pass transistor and on-card current source parts; and the connection of new off card components, including current source parts related to M1/M2,

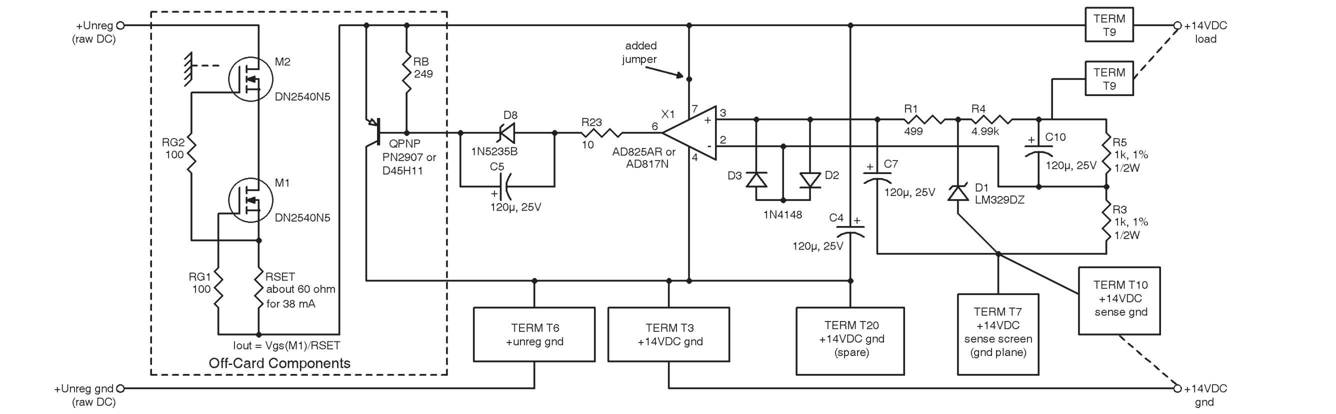

Figure 1: The positive shunt super regulator (SSR) circuit is based on "Improved Positive Regulator." It incorporates X1 op-amp supply bootstrapping and uses PNP control transistor and DN2540 cascode current source, both off card.

and shunt PNP transistor Q_{PNP}, plus R_B.

Note that what's shown isn't necessarily the last word as a functional circuit—it is but one example. The basic principles apply to *any* shunt-type regulator so used. And, importantly, *the above described conceptual distinctions between series and shunt regulation do apply to both solid-state and vacuum-tube circuitry*. Thus, it is both convenient and technically proper to note that you can use the DN2540 cascode circuit with sources of up to 400 V, and build yourself a superior shunt regulator—with and/or for tubes, or with and/for transistors.

So, that's my general answer as to what type of regulator I'd recommend for today's highest-quality audio designs. You may or may not agree with the importance of isolating the audio dynamic currents, with a shunt-type regulator. That's your choice of course, so you can decide which is best.

SHANNON: Do you have any advice for *audioXpress* readers who are considering their own audio DIY projects?


Photo 3: Walt Jung pictured in his home office, as he continues his historical research.

WALT: I'll echo advice that Ed Dell expressed years back, on making ice cream, "Always use good stuff!" Works for audio also—good stuff means the highest quality parts one can afford, applied sensibly. Hand-rubbed wood enclosures are also pretty and add a touch of class. That part's up to the readers. But I'd also add, first pick a good candidate project upon which to lavish the attention!

SHANNON: What projects are you currently working on?

WALT: A follow-on to the historical research alluded to earlier. That's about all I can say at the moment—but it promises to be even more rewarding, in the end (see **Photo 3**).

SHANNON: A lot has changed in audio technology during the past few decades. What changes do you consider positive? Any negative?

WALT: I'd say the digital transition has (on balance) been positive, but not without growing pains. For example, digital technology demands proper handling of high speed logic signals and is loaded with RFI/EMI pitfalls. Learning to deal with such environments has made our audio better, albeit after some pain. Even in non-digital equipment RFI can be an issue (e.g., rectifier noise pollution).

Certainly the Internet's emergence and the many audio websites are a plus to better communication. But this is only as good as the efforts put forth by the people using the new technology. The tools make it easier, but there is still work getting solid information out there in a useful and understandable fashion. Case in point: the earlier-cited Baxandall-Swallow type of current source, not at all well known in audio literature, but once understood, a powerful tool. *aX*