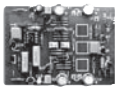


Musical Waveform Peak and Average Power Frequency Distributions

Analyzing four music selections, this author relates them to amplifier peak power demand, maximum SPL, high-frequency distortion, and, in two cases, sound quality.

By Dennis Colin

SPL tends to be judged on the basis of average power, but it's the peaks that are amplifier limited. So the higher the peak-to-average power ratio, the lower will be the SPL capability without clipping. And while most music has a significant HF rolloff in average power, HF peaks can be quite strong. In one selection presented here, the peak power at 4kHz and 14kHz is 5dB higher than that at any lower frequency. And, of course, amplifiers usually have the highest distortion at high frequencies and with sharp transients.

I analyzed four musical selections during a sustained maximum-volume segment for peak and RMS voltages—both directly and within ⅓ octave bands across the spectrum. I plotted the data in relative dB as peak and average power and tabulated it as a percentage of total peak power present within octave bands; the latter allows estimation of an amplifier's clean HF power capacity requirement.

DEFINITIONS

1. Peak Power

Since amplifiers are rated in average sine-wave power (not instantaneous crest power, which is double), and because most of the highest peaks from acoustic instruments look nearly sinusoidal (**Photo 1A**), it's consistent and convenient to use the average power (or RMS voltage) in the highest transient half-cycles, averaged or RMS'd over their duration (**Fig. 1**). Then $V_{PRMS} \approx V_P/\sqrt{2}$. This voltage, when squared and divided by some load resistance, results in the average power of the transient.

V_{RMS} is the long-term RMS voltage (1.1s averaging time in my measurements), which when similarly processed results in the long-term average power. Then $(V_{PRMS}/V_{RMS})^2$ is the ratio of the maximum sine-wave amplifier power needed to the average waveform power. Maximum sine-wave power (half the instantaneous power at the peaks) is used to be consistent with standard amplifier power rating practice.

In this article, the term "peak power" means "maximum sine power," not absolute peak power (twice as much). So defined, the peak/average power ratio in dB is 20log (V_{PRMS}/V_{RMS}). The crest factor (V_P/V_{RMS}) expressed in dB is 20log (V_P/V_{RMS}), 3dB higher than the as-defined peak/average ratio.

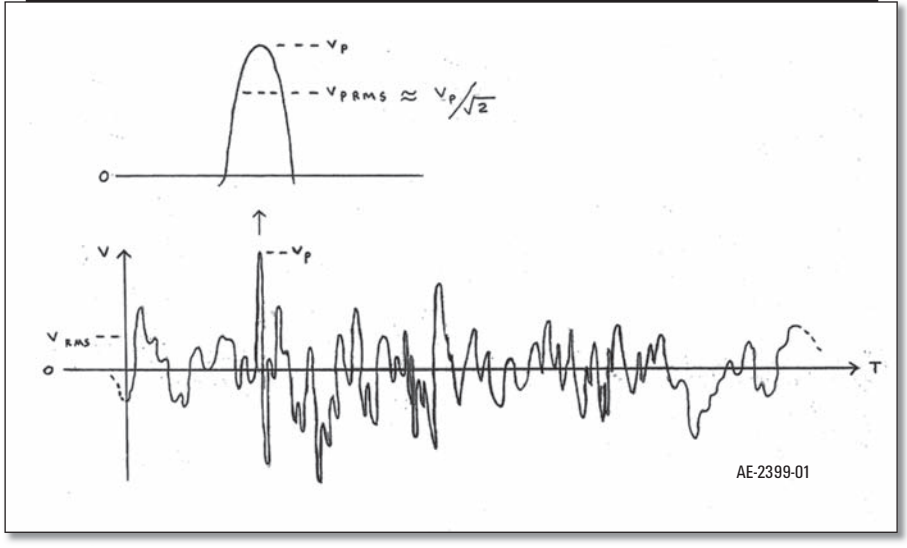
2. Average Power

Obviously with music this depends on the averaging time. The ear (also the eye) has an integration time of about 1/20 second. Events repeating more slowly than about 20Hz are resolved as a time sequence, or rhythm. So a power averaging (or V^2 averaging for RMS voltage) time of 1/20s is a lower limit, and this duration also includes one cycle of the lowest audio frequency.

But in observing the output of an RMS to DC converter with variable averaging time constant, 1/20 or even 1/10s allowed too much LF ripple or "flickering" on the output to obtain stable readings. Also, some peaks would undesirably increase the supposedly average result viewed on a meter.

With average times longer than about 0.5s, readings were stable and

FIGURE 1: Definitions.

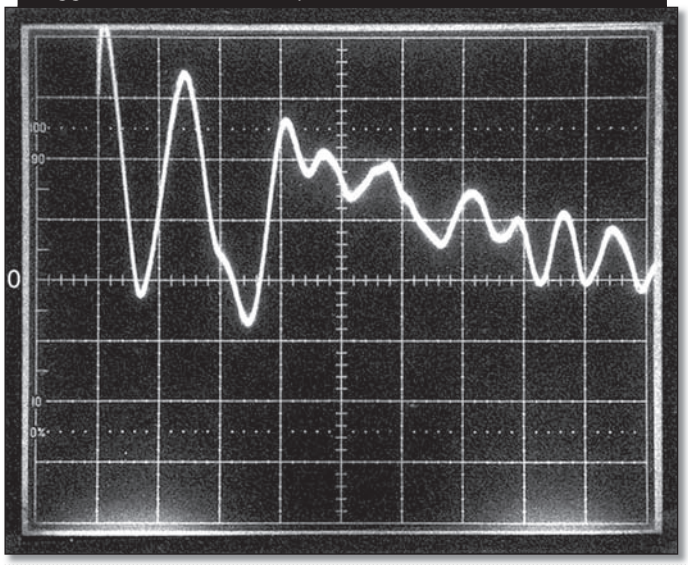


didn't change significantly with longer average times, if the perceived SPL was constant. I then wired the RMS detector for switchable 0.1 or 1.1s averaging times. No reason for the 1.1 figure (resistors and caps on hand, you know). For all but one measurement, I used the 1.1s averaging for RMS voltages.

AND NOW, THE PERFORMERS

1. *Emmanuel Chabrier "España," Ansermet/L'Orchestre de la Suisse Romande*, Decca 448 576-2: A very lively piece, recorded in 1964 directly onto two-track tape. Probably not coincidentally, the audio waveforms have high peak/average ratios especially at high frequencies, and the sounds are very dynamic with natural "bite." Also, the stereo depth puts many modern recordings to shame. (Ask Ed Dell how he likes the Ansermet/Suisse Romande recordings!)
2. *Handel "La Réjouissance,"* *HiFi News* HFN020: A horn fanfare with (not too loud) fireworks. Even with the latter,

PHOTO 1A: *All My Exes Live in Texas* scope 200mV/div, triggered on snare drum peak (0.2ms/div).



strangely, the peaks and peak/average ratios were much lower than in *España*. And while the performance was dynamic, the sound seemed muted and the spectrum (even of peaks) was much more rolled off above 2kHz.

3. *John Pizzarelli: "If Dreams Come True,"* Telarc SACD-63546: Very well recorded popular song with George Schering on piano.
4. *George Strait "All My Ex's Live in Texas,"* MCA MCAD-5913. A great performance and clear recording, except for a highly (studio) boosted 3–18kHz content. Serving as an extreme example of HF peak power demand, the highest peaks (from a rhythmic snare drum beat) are at 4kHz and 14kHz, and at 5dB above the rest of the spectrum. At 14kHz the peak/average ratio is about 25dB, a 316:1 power ratio. About 33% of the peak amplifier power output will be in the 5kHz–20kHz band.

HIGHEST TRANSIENT WAVEFORMS

The high snare drum peaks in George Strait's recording allowed consistent scope triggering while also showing the complex waveform summation of the multiple instruments playing (**Fig. 2**); **Photos 1A–1C** present this on different time scales.

Photos 2A and **2B** show stereo X–Y crossplots (Lissajous figures). They aren't single sweeps as in **Photos 1A–C**, but 1/8s exposures where the dense average-signal central regions saturated the film, because high scope brightness was needed to capture (some of) the peak excursions.

Lissajous displays also reveal left-right correlation: mono produces a 45° straight line; a 90° shifted L–R sine wave makes a perfect circle, and natural-sounding stereo music generates a round, almost spherical-looking pattern as in **Photo 2B**, from *España*. This recording has excellent stereo depth and imaging.

LONG SWEEP STORAGE SCOPE WAVEFORMS

Photos 3–10 show a single sweep of 1s

TABLE 1: Audio Waveform Properties, 10S Interval of Loudest Playing.

	Chabrier	Handel	Pizzarelli	Strait
Peak Voltage	1500mV +2.7dBm	500mV −6.8dBm	850mV −2.2dBm	900mV −1.7dBm
RMS Voltage 1.1s TAVG	275mV −9dBm	98mV −18dBm	155mV −14dBm	98mV −18dBm
Crest Factor $= V_p/V_{RMS}$	5.45	5.10	5.48	9.18
Sine Weighted Peak/Avg Power Ratio	14.8:1 11.7dB	13.2:1 11.2dB	15.1:1 11.8dB	42.7:1 16.3dB

PHOTO 1B: *All My Exes Live in Texas* scope 200mV/div, triggered on snare drum peak (1ms/div).

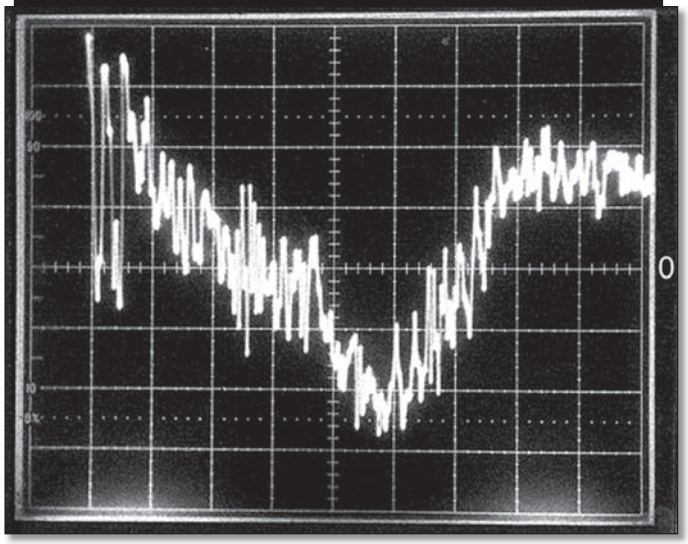


PHOTO 1C: *All My Exes Live in Texas* scope 200mV/div, triggered on snare drum peak (5ms/div).

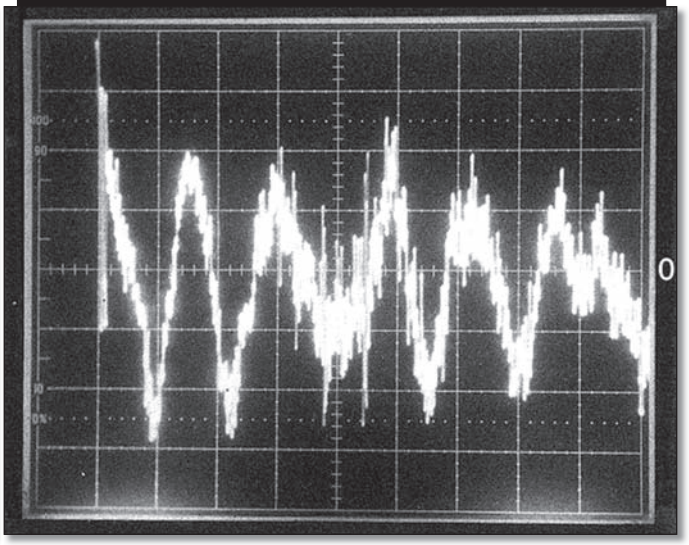


FIGURE 2: Test setup, unfiltered audio.

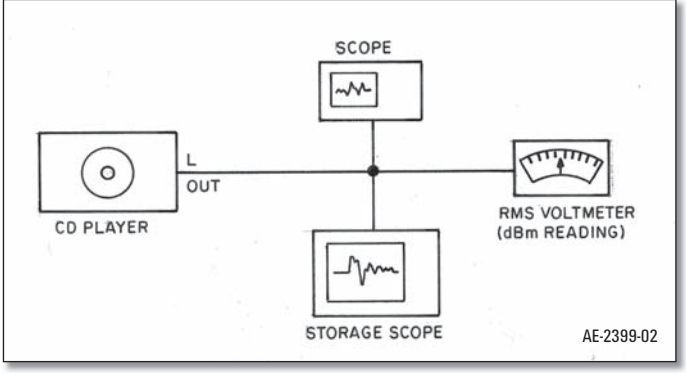
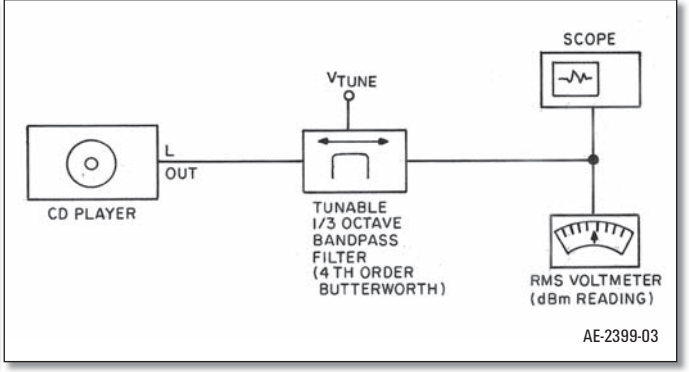


FIGURE 3: Test setup, 1/3 octave filtered audio..



(**Photos 3–6**) and 10s (**Photos 7–10**) for a steady high-volume segment of the selections. Of note in the George Strait country song in **Photo 10** are the repetitive high peaks (containing very high relative power even at 18kHz); these are the snare drum accents.

TABLE 2: Chabrier "España"—Highest outputs through ⅓-octave BP filter during 10s interval of loudest playing.

Peak Frequency	mV	RMS dBm	dBm
20Hz			
25	3.5	−50	
31	7	−44	−53
40	17	−36	−44
50	42	−28	−32
63	77	−23	−30
80	210	−14	−22
100Hz	180	−16	−24
125	330	−10	−18
160	450	−8	−19
200	440	−8	−17
250	420	−8	−18
315	500	−7	−18
400	320	−11	−20
500	250	−13	−22
630	230	−14	−23
800	240	−13	−26
1kHz	260	−12	−24
1.25	280	−12	−24
1.6	230	−14	−26
2	210	−14	−25
2.5	240	−13	−26
3.1	210	−14	−27
4	170	−16	−28
5	140	−18	−30
6.3	160	−17	−30
8	180	−16	−30
10kHz	240	−13	−29
12.5	350	−10	−28
16	240	−13	−30
20kHz	130	−19	−38
	RSS Sum = 1413mV (+2.2dBm)		Power Sum = −8.6dBm
Unfiltered Audio:	1500mV (+2.7dBm) (peak)	−9dBm	(RMS)

$$\frac{\text{Sine weighted peak power}}{\text{1.1s average power}} = 4.8 = 11.7\text{dB}$$

crest factor = 5.45 = 14.7dB
(11.7dB more than a sine wave)

PEAKS AND AVERAGES OF AUDIO WAVEFORM

The highest peaks, RMS values, ratios thereof (crest factors), and peak/average power ratios are shown in **Table 1**. For the peaks, the dBm values (re 0dBm = 0.775V RMS, 1.095V peak sine) are calculated for a sine wave with the same peak voltage as the observed musical waveform peak. This is consistent with the stated definition of peak power as the average power within the highest peaks (which most often resemble sinusoidal half-cycles). This is also consistent with the average sine-wave power rating of amplifiers.

⅓ OCTAVE FREQUENCY SPECTRUM

The ⅓ octave filter (**Fig. 3**) was stepped through the audio spectrum, noting the highest peaks and RMS voltages at each filter frequency. Results are presented for *España* in **Table 2**.

Figures 4–7 show (top traces) the spectrum of

PHOTO 2A: Stereo Lissajous pattern, scope 200mV/div, X=left, Y=right (*All My Exes Live in Texas*).

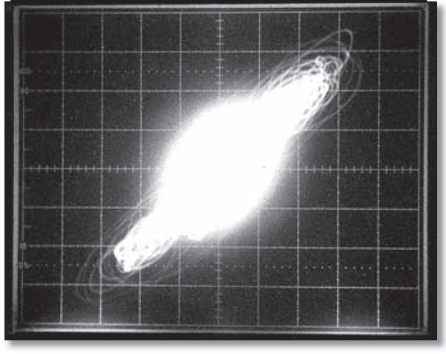
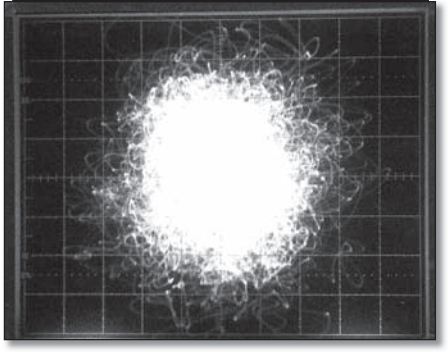


PHOTO 2B: Stereo Lissajous pattern, scope 200mV/div, X=left, Y=right (*España*).



the highest peaks, manually plotted from this data; lower traces are the averaged values. Note that with peak power as defined here, the "peak" and "average" traces would be the same for a sine-wave signal.

PHOTO 3: *España*, 1s sweep.

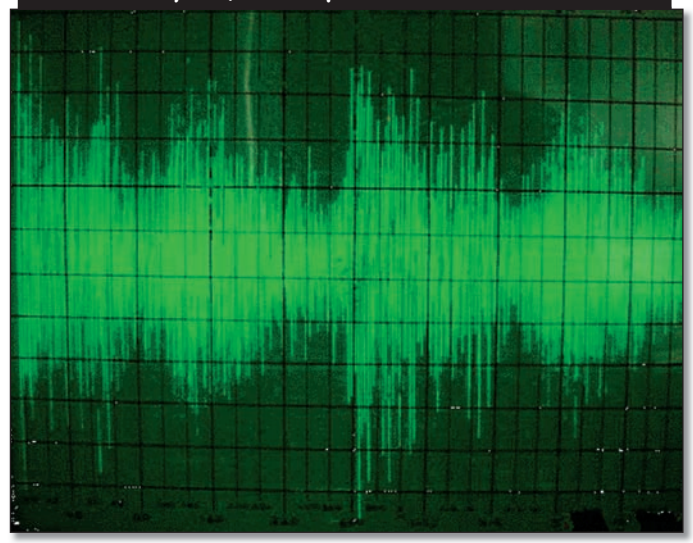


PHOTO 4: *La Réjouissance*, 1s sweep.

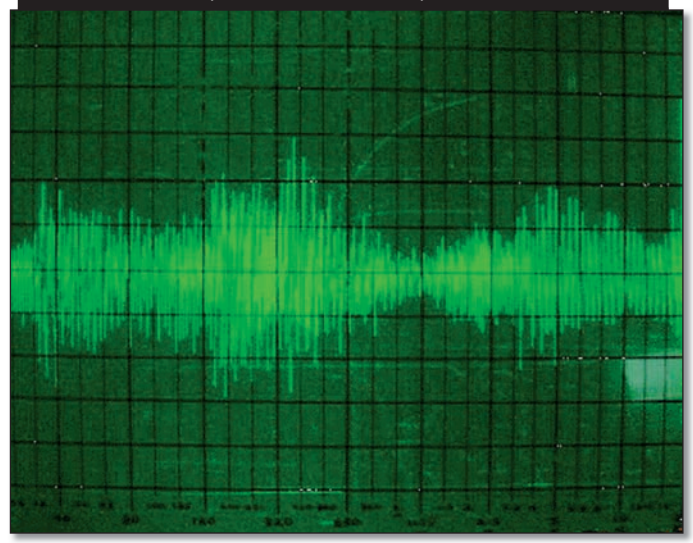
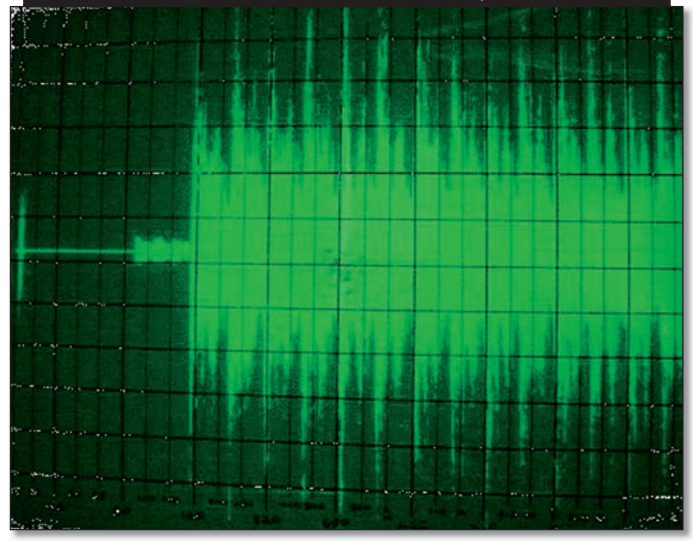


PHOTO 5: *If Dreams Come True*, 1s sweep.



NOTABLE FEATURES

1. The most surprising feature is the HF power in the peaks of George Strait's song (top trace, **Fig. 7**). I'd bet that someone in the studio cranked up two HF EQs to get peak power at about 4kHz and 14kHz, which is 5dB higher than at any lower frequency.
2. In **Fig. 7** only, I plotted the RMS level with 0.1s averaging time in addition to the 1.1s average RMS shown in all four selections. Note that around 200Hz, the shorter-time average nearly equals the peak. This implies a nearly sinusoidal waveform, of nearly constant amplitude within the 0.1s averaging time.

Such a signal can be produced by the upper notes of a bass (and standard) guitar: 200Hz is in the upper range of a bass guitar, where harmonics are most attenuated. Such notes can have nearly sinusoidal waveforms.

3. Note that only in the Handel piece (**Fig. 5**) does the spacing between

the peak and average traces stay nearly constant over the whole frequency range. With the other selections, although the average traces roll off at high frequencies, the peak traces roll off much less or actually rise (**Fig. 7**), producing a greatly expanded spacing between peak and average at the highest frequencies. This is because most of the peak power in the high treble is from short-duration percussion accents (short relative to their repetition time); this low duty-cycle results in (for example, **Fig. 7** at 12kHz) a 25dB peak/average ratio (about a 316:1 power ratio).

PHOTO 6: *All My Exes*, 1s sweep.

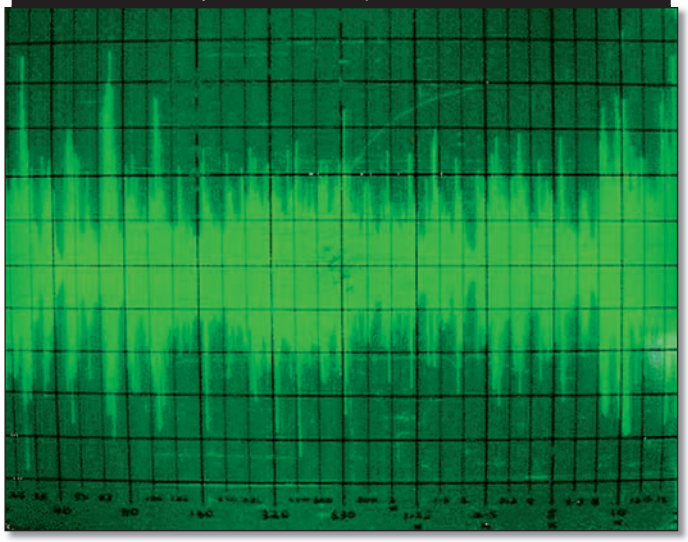


PHOTO 7: *España*, 10s sweep.

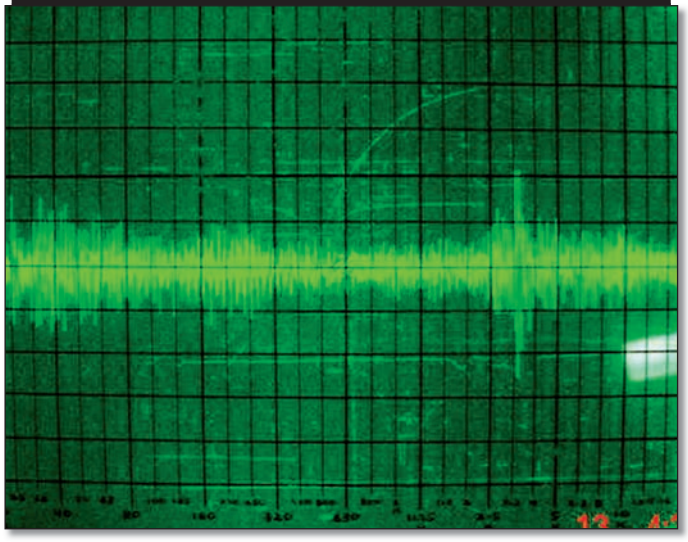
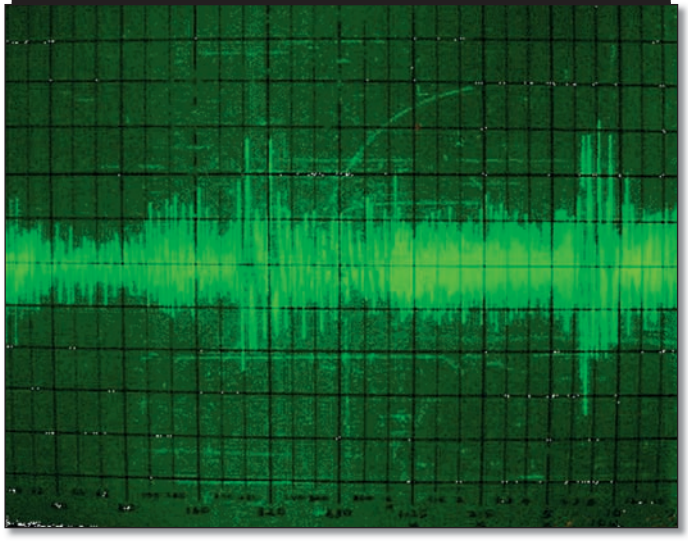


PHOTO 8: *La Réjouissance*, 10s sweep.



4. Below about 1.2kHz, the peak/average ratio in all selections is mostly within a 5–10dB range. Considering just for now the 3dB "crest factor" of a sine wave (twice the average power at the sine peaks), the crest factor of the signals below 1.2kHz is approximately 8–13dB, similar to that of Gaussian noise.

PERCENTAGES OF PEAK POWER IN OCTAVE BANDS

In **Table 2**, the filtered band peak output voltages were RSS (root-sum-square) totaled; this is valid for uncorrelated signals, such as different frequencies or noise sources. The result (1413mV) is

within 0.5dB of the 1500mV input peak.

Next (not shown), I calculated RSS sums within octave bands and tabulated, in each band, squaring this octave-peak voltage and dividing by the 1500mV input peak squared. This result is a power ratio, the fraction of peak signal power present in a particular octave band.

Adding these octave percentages was within the same 0.5dB as with the **Table 2** results, of equaling 100% of the signal power; for convenience they were scaled to total 100% in **Table 3**.

Note that the validity of the calculations depends on different frequency peaks occurring reasonably simultaneously: consider, for example, an alternating duet between a bass guitar and a flute, of equal signal voltage for convenience. With this frequency separation, two separate sets of filtered bands will produce alternating, not simultaneous, outputs. So it would be wrong to sum them and expect this to equal the input signal; the bass range and the flute range powers would each be 100% of the input signal power, inappropriately "totaling" 200%. But with these four selections, the sums were within 0.5dB of the input power, so peaks across the spectrum must be occurring reasonably simultaneously.

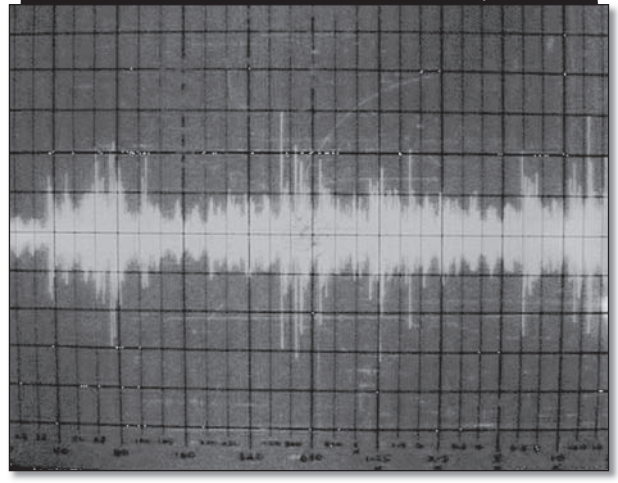
TABLE 3: Percentages of peak audio power present in each octave band.

Octave Band	Chabrier	Handel	Pizzarelli	Strait
20–40Hz				
40–80Hz	1.5	0.8	8.1	2.4
80–160Hz	13.3	6.9	21.7	6.7
160–315Hz	29.9	26.2	22.8	8.1
315–630Hz	15.8	24.0	22.1	8.3
630Hz–1.25kHz	9.6	17.8	12.3	8.3
1.25–2.5kHz	8.2	15.6	4.9	9.5
2.5–5kHz	5.6	6.8	3.2	23.4
5–10kHz	4.8	1.7	2.9	13.6
10–20kHz	11.3	0.2	2.0	19.7

TABLE 4: Percentages of audio power present in each octave band, Chabrier *España*.

Octave Band	Peak Power %	Average Power %
40–80Hz	1.5	3.4
80–160Hz	13.3	20.6
160–315Hz	29.9	35.1
315–630Hz	15.8	18.7
630Hz–1.25kHz	9.6	7.7
1.25–2.5kHz	8.2	6.2
2.5–5kHz	5.6	3.7
5–10kHz	4.8	2.2
10–20kHz	11.3	2.4

PHOTO 9: *If Dreams Come True*, 10s sweep.



This is not surprising, since in a musical climax or (especially) a strong rhythmic accent, all the instruments contributing would likely play loudly and in as close timing as possible.

Table 4 shows, for comparison, the octave band average power distribution for the *España* selection. Note that below about 600Hz the average power has a larger fraction than the peak power, but vice versa above 600Hz.

SONIC EFFECTS OF IM ON HIGH-FREQUENCY TRANSIENTS

With harmonic distortion, even-order is accepted as less objectionable than odd-order. Not so for high-frequency IM distortion. Consider a transient—say, mostly occupying an 8-12kHz, BW—of high peak power.

The maximum range of third-order IM products is 2(8kHz)-12kHz, and 2(12kHz)-8kHz, or 4-16kHz. So with enough IM the original transient-signal BW of 4kHz becomes tripled,

spread out to a 12kHz BW. Still, within the HF range above 4kHz and of very short duration, a moderate amount of IM could be unnoticeable.

But second-order IM is very different. Here the products are simple frequency sums and differences, and the range of difference products from a continuous 8–12kHz signal band is zero (DC) to 4kHz. Enough second-order IM, or asymmetrical limiting, will produce an audible "spectral downwash," a crunchy sound extending into the lowest bass. This is why SET amps should not be overdriven.

AMP HIGH-FREQUENCY PEAK POWER

With an amp playing just below clipping, it's interesting to know how much of the amp's HF power capacity (often below normally stated midband power rating) is being used up; how much margin (if any) is there?

The extreme example with top octave studio boost needs the following fractions of peak power in the stated bands: 5% (16–20kHz), 20% (10–20kHz), and 33% (5–20kHz). There could be recordings with even higher percentages, such as close-miked small bells or chimes, special effects, synthesizers, and so on. Also, SACDs (100kHz response) may contain significant ultrasonic content.

But it seems unlikely for audiophile-quality recordings to have more than one-third of the peak power above 5kHz; the *España* selection has about 16%, and it's a very (and naturally) brilliant sound.

Flash back to *Glass Audio* 5/2000, where the Antique Electronic Supply AE-25 "Super Amp" is reviewed. Rated at 15W/channel triode, Charles Hansen measured only 2.3W at 3% THD at 20kHz (*p. 35*). That's 15% of rated power. But even the George Strait recording needs only 5% in the narrower ⅓ octave 16–20kHz band.

Charles Hansen measured 19 +20kHz IM at 0.98% with 6V p-p, 8W, an instantaneous crest power of 1.125W, and average power of 0.281W (4:1 ratio, 2:1 voltage crest factor for an equal-amplitude two-tone signal). The ±3V peaks would correspond to a 0.56W single sine wave (at 19 or 20kHz); 0.56W is 3.7% of rated power for 1% IM distortion at 19-20kHz.

PHOTO 10: *All My Exes Live in Texas*, 10s sweep.

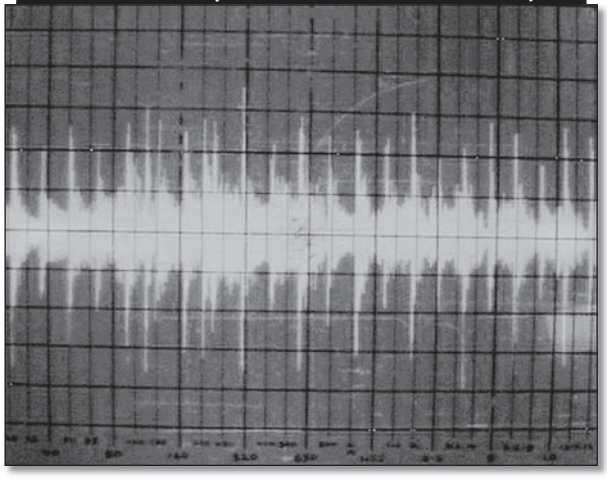
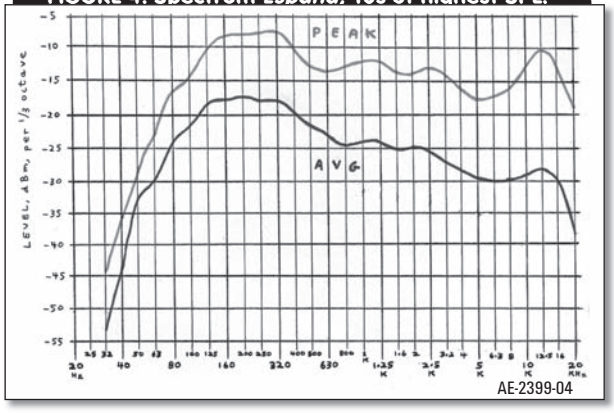


FIGURE 4: Spectrum *España*, 10s of highest SPL.



Enough trying to mathematically predict the sound: Ken and Julie Ketler, whose many reviews testify to their sonic perceptiveness, gave the AE-25 a generally praise-filled review. One comment possibly relating to this article, comparing the AE-25 with a Valve Audio Lab VAA-100ES 30W p-p amp: "The snares on the bottom drumheads are much more clearly defined with the Super Amp. The difference is particularly noticeable during quiet sections." Regarding the latter sentence, I would guess

that at louder levels the AE-25 runs out of HF power, degrading performance to that of the comparison amp (or the snare drum at louder levels overloaded the recording system or other component).

PEAK POWER VERSUS SPL

Suppose you desire a maximum SPL of 90dB—loud, but not that loud—and your speakers' sensitivity is 86dB, 1W, 1m. From ten feet away, this would be 76dB with 1W anechoically, but with typical room reinforcement I measured a drop of only 3dB. So at the listening position, each speaker delivers 83dB SPL at 1W. With (generally nonphase correlated) stereo, each speaker needs to deliver 87dB SPL for the desired 90dB example. This requires 4dB more than 1W, or 2.5W average power per channel.

With the George Strait recording, peak (sine-weighted) power is 42.7 times the average, so 107W per channel is needed for a 90dB average SPL without clipping. With the Handel recording, 33W per channel is needed.

Here's an extreme example: You heard an orchestra playing *España* with 105dB SPL climaxes (remember that perceived SPL relates to average power; the waveform peaks would be 11dB higher), and you wish to reproduce this level in your listening room with 86dB 1W/1m speakers. You would need about 1200W/channel, of which about 200W peaks will be in the 5-20kHz range.

And to hear from all your Ex's in Texas at 105dB, you'd need 3500W/channel! *aX*

FIGURE 5: Spectrum *La Réjouissance*, 10s of highest

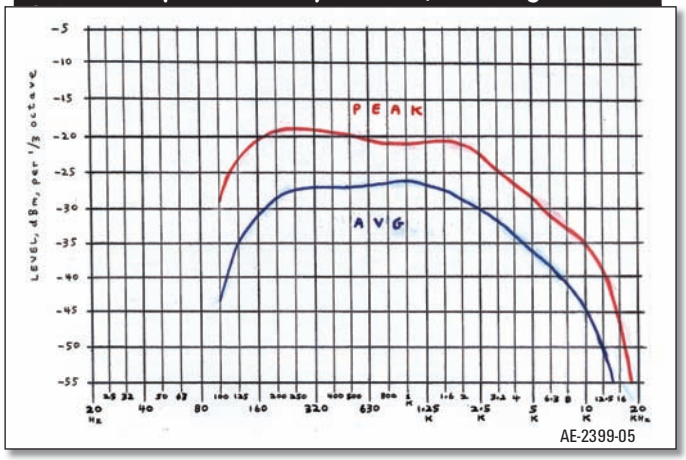


FIGURE 6: Spectrum *All My Exes Live in Texas*, 10s of highest SPL.

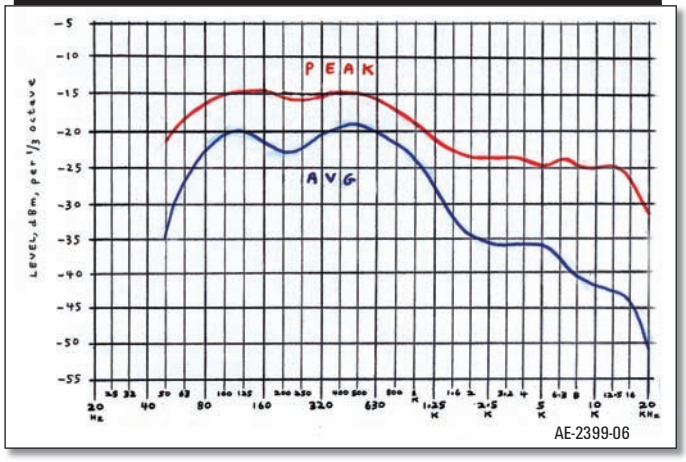


FIGURE 7: Spectrum *All My Exes Live in Texas*, 10s of highest SPL.