Part 2

REGULATORS FOR HIGH-PERFORMANCE AUDIO

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The actual testing of various regulators for this article was divided into three major tests for LR (line rejection), noise, and Z_O (output impedance), which are further divided by the various regulator topologies, and then into positive and negative forms. The aggregate regulator count was 13 separate circuits under test, described in the following sections, and broadly organized into the separate LR, noise, and Z_O test series.

Line Rejection Tests

The basics of the LR tests, summarized in Part 1 (Fig. 2a), can be illustrated with a simple example using the 7815 three-terminal regulator device. Powered up as shown in Fig. 2a, it uses an 18V DC source and standard 1V P/P AC input signal as provided by the positive rail driver/regulator (Fig. 6). The loading is C1 = 100µF and I1 = 150mA.

Figure 10 is a three-trace plot resulting from the LR tests on the 7815. It uses a horizontal frequency scale of 20–200kHz and a vertical scale of −150 to +10dB. This general procedure similarly applies to other regulators. For test calibration, the TP OUT driver signal is monitored with the analyzer B input, and is set to 0dB while running "REG-LR.TST" (using the analyzer's F4 function key, as explained in Part 1). With a given regulator, the analyzer input is thus referenced to 0dB = 1V P/P, for a reference V_{IN} frequency sweep trace (a).

Next, we run a second zero signal GND reference trace, with the analyzer input connected to the regulator TP GND test point. *Figure 10* shows this as the lower (varying) trace (c), which ranges from an isolation of about 105dB at 100kHz, down to the 130dB range below 1kHz. This trace represents the test setup noise floor, and thus is the maximum possible LR measurement for a specific test cell location (there is some variation across the 13 sites of the test breadboard, mostly at the higher frequencies). The (a) and (c) traces are not repeated in subsequent LR plots, but were recorded for reference purposes.

The V_{OUT} trace (b) shows the performance of a given regulator measured at the regulator TP OUT test point. In the 7815 example, the regulator isolation is more than 70dB at very low frequencies, and decreases to about 45dB at 100kHz. The object, of course, is to maximize regulator LR across this range of frequencies. The subsequent plots show the V_{OUT} (only) traces of various regulators, grouped by their respective families. The V_{IN} and GND reference traces are not shown but may be assumed comparable to *Fig. 10*.

The three-terminal *positive* regulator group's LR in *Fig. 11a* includes the 7815 *fixed* regulator (c), plus the 317 (b) and 1085 (a) *adjustable* regulators, connected as noted in Part 1. These adjustable versions are appreciably better than the 7815, except at the extreme upper frequencies. The 80–90dB isolation at low frequencies is possible due to the bypassing of the device adjust pin, which effectively lowers the AC noise gain of the IC, thereby increasing LR. Lacking the option of this AC bypass capability, fixed voltage three-terminal regulators such as the 7815 generally have worse LR than their adjustable counterparts.

The three-terminal *negative* regulator group LR in *Fig. 11b* includes the 7915 fixed regulator (c) and the 337 (b) and 1033 (a) adjustable regulators, connected as in Part 1. Here the adjustable regulators are still better than the fixed voltage 7915 at the very low frequencies, but this reverses above 1kHz, with the 7915 appreciably better at 100kHz.

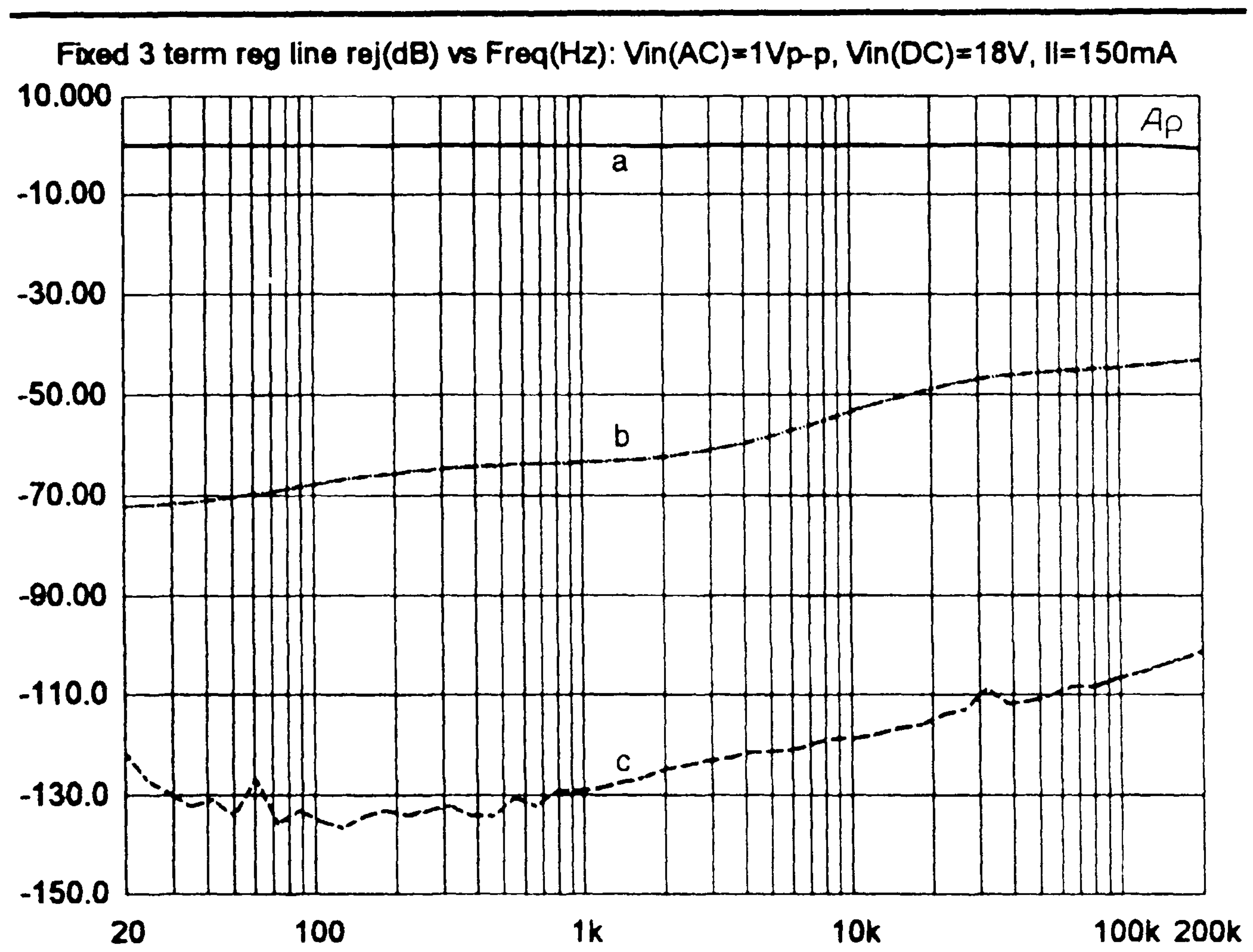

FIGURE 10: Fixed three-terminal 7815 regulator LR performance, a) V_{IN} = 0dB; b) V_{OUT}; c) GND reference.

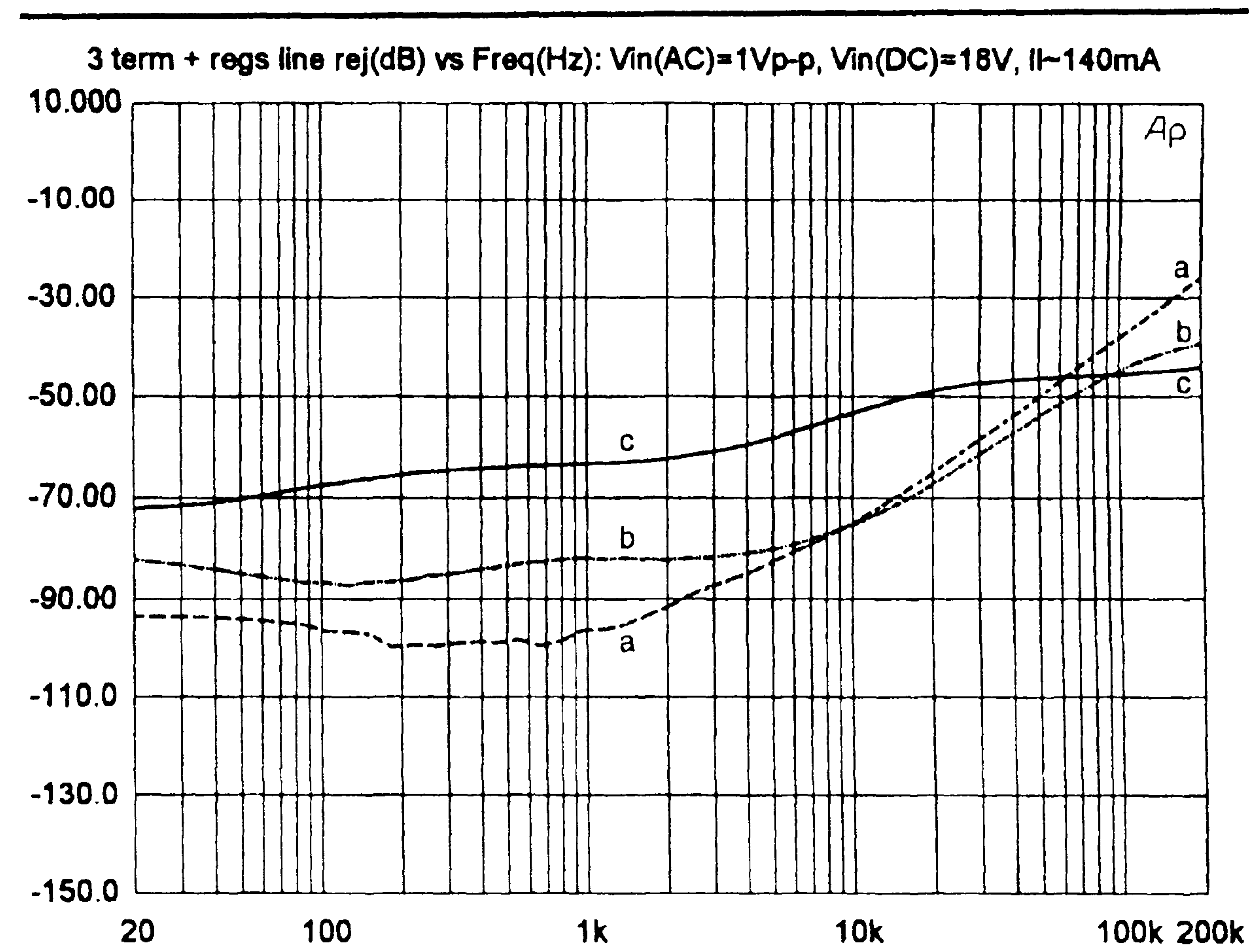

FIGURE 11a: Three-terminal positive regulator LR, a) 1085; b) 317; c) 7815.

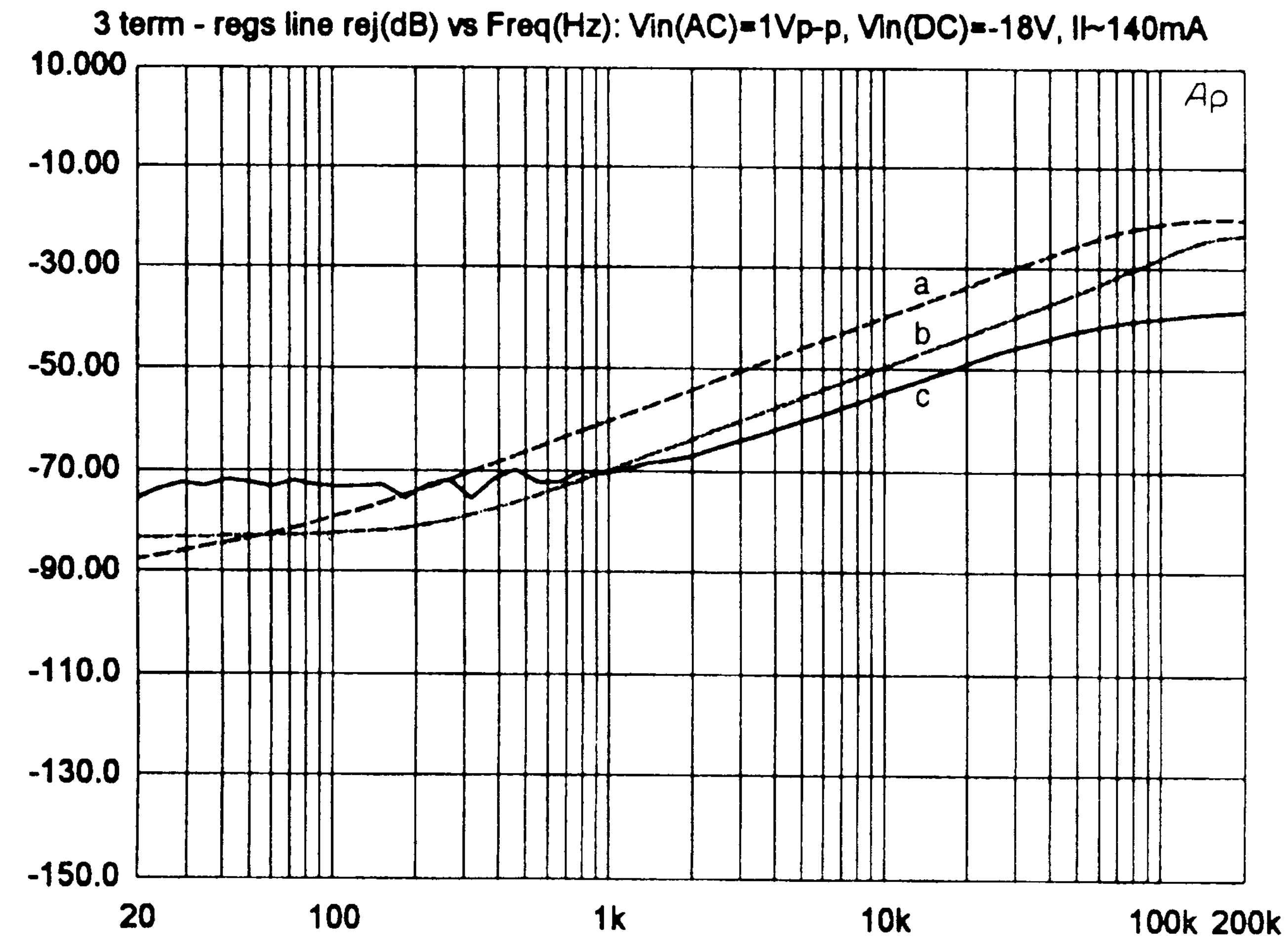

FIGURE 11b: Three-terminal negative regulator LR, a) 1033; b) 337; c) 7915.

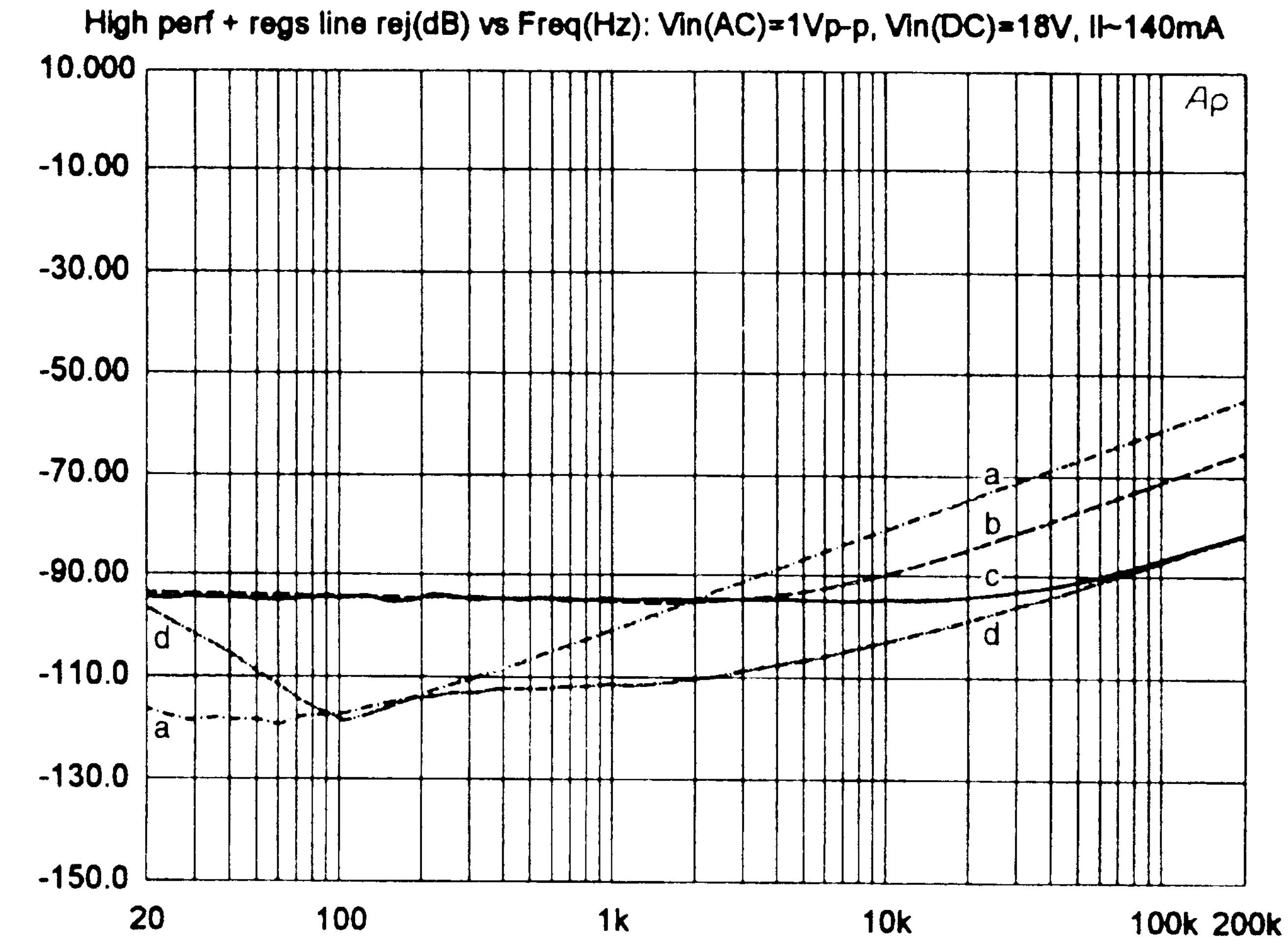

FIGURE 12a: High-performance positive regulator LR, a) AD797 (Fig. 8a); b) AD848 (Fig. 8a); c) POOGE 5.51 (Fig. 3); d) Sulzer circuit (Fig. 7a).

High Performers

Test results for the high-performance positive and negative regulator circuits (*Figs. 12a* through *12c*), as a group, show much higher LR, and also maintain this high rejection to higher frequencies than do the three-terminal types. Within the 20Hz–20kHz audio band, results of 90dB or greater are common in the high-performance group, with some circuits achieving isolation of 70dB or more at 100kHz. The very best regulators achieve 90dB or more at all frequencies, increasing to in excess of 100dB within the audio band.

In *Fig. 12a*, the Fig. 3 POOGE 5.51 regulator (c) has a remarkably flat LR of better than 90dB, up to about 100kHz. Two examples of the Fig. 8a circuit's performance are shown, using the AD797 (a) and AD848 (b) op amps. The AD848 attains about 90dB or more within the audio band, decreasing to 70dB at 100kHz. The AD797 achieves about 120dB at very low frequencies, decreasing to about 60dB at 100kHz. For these comparative conditions, the Sulzer circuit of Fig. 7a (d) achieves the best characteristics above 100Hz, decreasing to just under 90dB at 100kHz.

One reason for the excellent wideband LR of the Fig. 7a circuit is that the supply line to the op amp is passively decoupled, which enhances the op amp's inherent noise rejection above the R1-C2 corner frequency. In the data of *Fig. 12a*, the AD848 and AD797 op amps were *not* decoupled. When the optional Fig. 8a R8-C6 network is not used, the LR simply reflects that of the basic op amp.

The performance of the Fig. 8a circuit improves dramatically using both of these op amps with the network (*Fig. 12b*). The a and b curves reflect the same LR data for this AD797 and AD848 as displayed in *Fig. 12a* (that is, no decoupling). However, with the 22Ω/120µF filter active, the LR of the Fig. 8a regulator using either device increases to more than 120dB at 1kHz and 90dB at 100kHz, as shown in the two lower curves (c and d). The AD797's LR at low frequencies is superior, and approaches the noise floor.

Therefore, for the circuit of Fig. 8a (and also for its Fig. 8b complement), the best wideband LR performance is achieved with the optional noise filter in the op amp supply line. Because of the current drive mode used with the op amp, this supply line filter has a minimal effect on overall regulator dropout. In sum, there are two caveats to using this filter: the aforementioned (Part 1) potential degradation in LF response

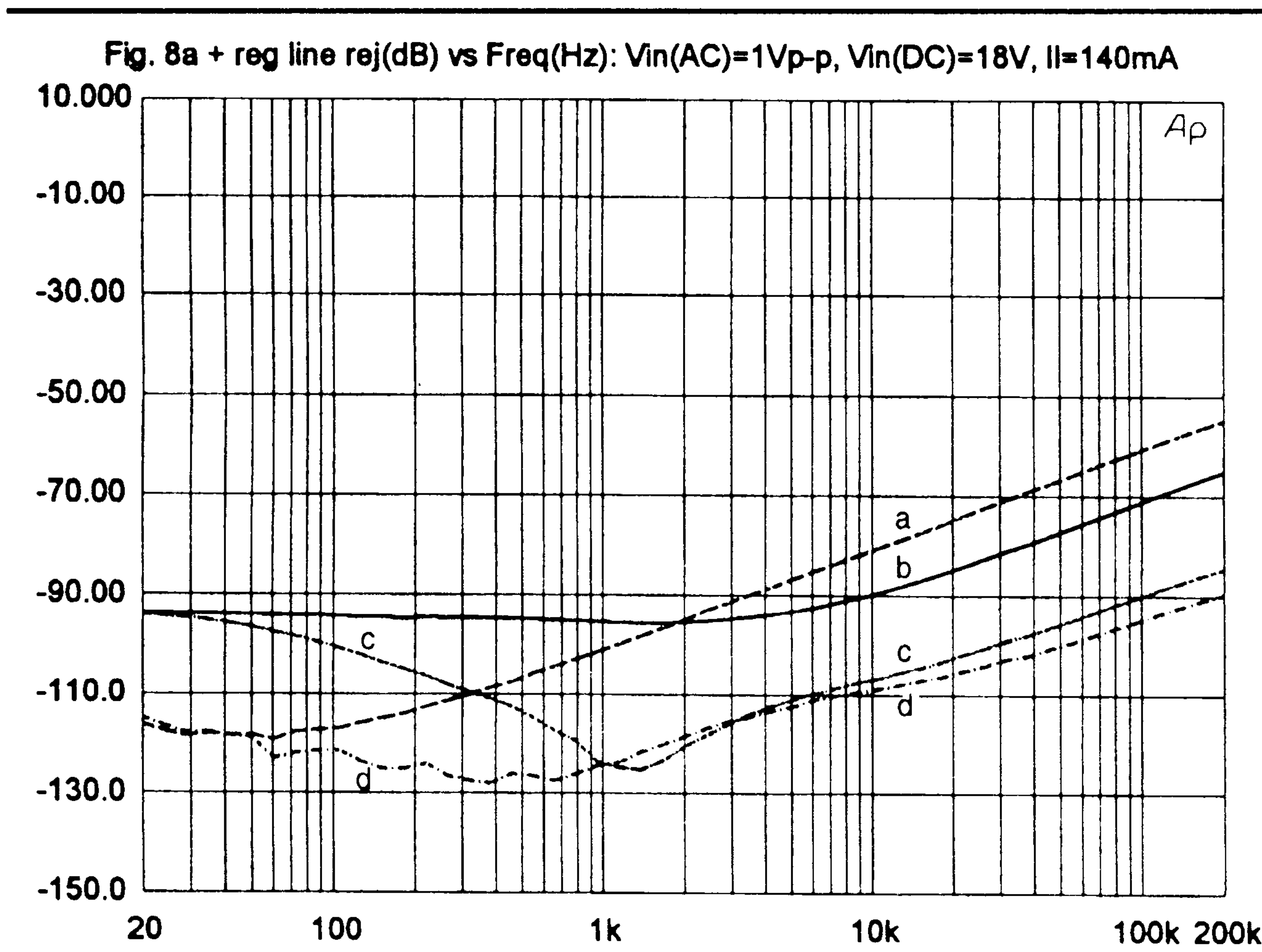

FIGURE 12b: Decoupling effects on LR (Fig. 8a), a) AD797; b) AD848; c) AD848 with decoupling; d) AD797 with decoupling.

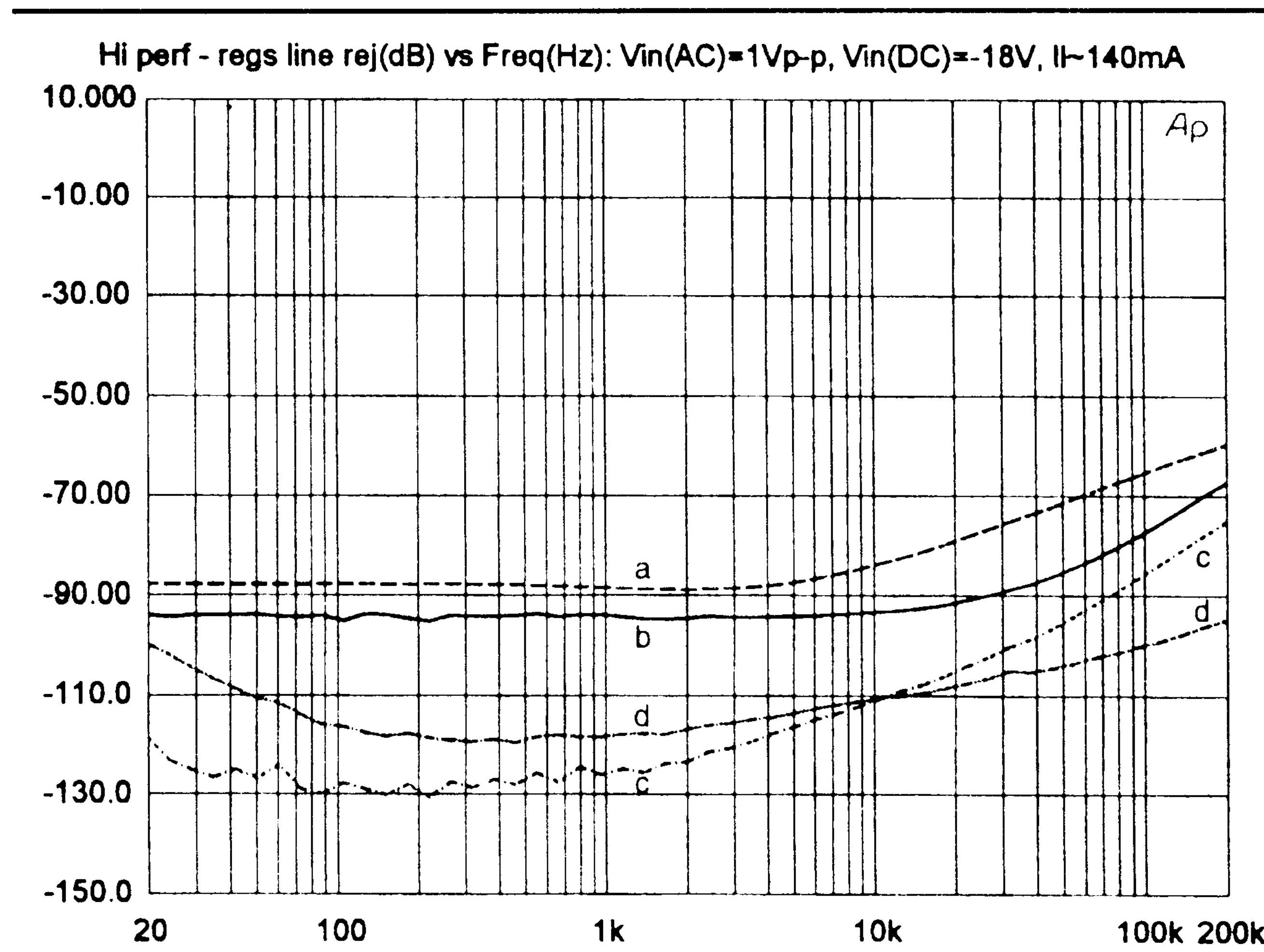

FIGURE 12c: High-performance negative regulator LR, a) AD848 (Fig. 8b); b) POOGE 5.51 (Fig. 4); c) AD797 (Fig 8b); d) Sulzer circuit (Fig. 7b).

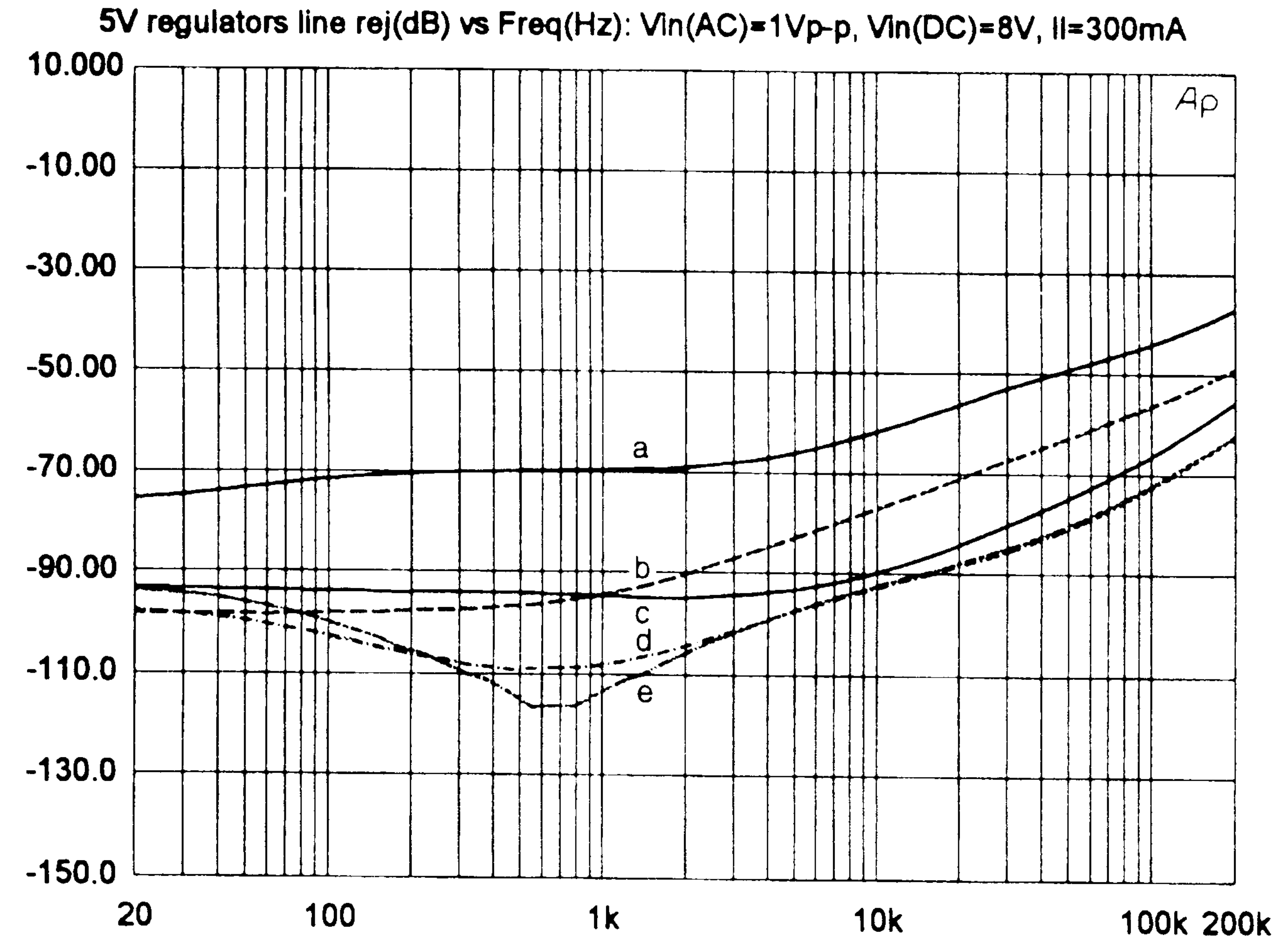

FIGURE 12d: 5V regulator LR, a) 7805CT; b) AD797 (Fig 9); c) AD848 (Fig. 9); d) AD797 (Fig. 9, bypassed); e) AD848 (Fig. 9, bypassed).

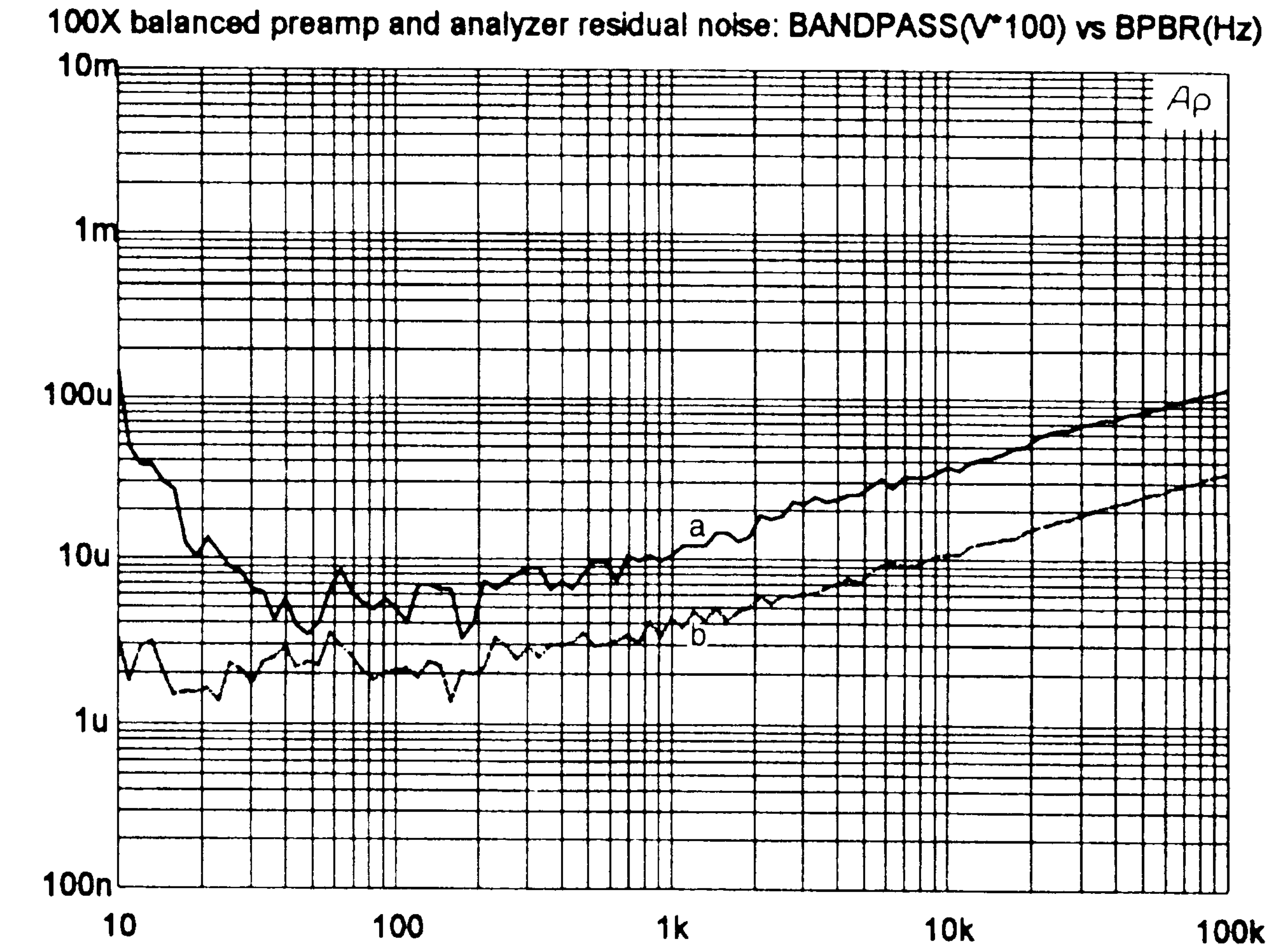

FIGURE 13b: Residual noise results, a) System One ×100; b) preamp.

(due to the supply Z increase) and the dropout voltage increase (a few hundred millivolts).

Negative Regulators

Op amps typically differ in their ability to reject power supply noise between the positive and negative supply rails. In these op amp regulators, just one supply line is relevant, with the other supply terminal grounded. As a result, the LR performance of otherwise mirror-imaged regulator circuits can and will vary substantially (for example, the Fig. 8a and 8b circuits).

Figure 12c shows LR results for the negative high-performance regulator group, with conditions generally similar to those of *Fig. 12a*. The AD848 (a) and AD797 (c) are operated within the Fig. 8b circuit *without* decoupling, while the Fig. 7b Sulzer regulator (d) and the Fig. 4 POOGE 5.51 regulator (b) are also tested.

Although the POOGE 5.51 negative regulator still shows a quite high and flat LR, all three op-amp-based negative regulators differ in their LR characteristics, vis-à-vis the data of *Fig. 12a*. This different op amp plus/minus supply rejection works to strong advantage for one form of the Fig. 8b negative regulator, i.e., the AD797. The Sulzer Fig. 7b circuit performance changes somewhat as compared with that of Fig. 7a, but overall it is still excellent.

The AD848 in the Fig. 8b circuit without decoupling does not perform as well as the AD848 positive counterpart of Fig. 8a, when similarly configured. However, the decoupling option does improve the LR substantially (data not shown). Where maximum LR is critical, the AD797 in the Fig. 8b circuit offers highest performance in the audio band.

The results of several 5V logic regulators for LR (*Fig. 12d*) illustrate curves for the AD797 and AD848 in the Fig. 9 circuit under two conditions, plus data for the standard 5V logic regulator, the 7805CT. The test conditions include a DC input voltage of 8V and a load current of 300mA, with the standard 1V P/P AC signal.

The 7805's LR (a) for this test is 55dB or better within the audio band, decreasing to about 45dB at 100kHz. This roughly compares to the 7815. The op-amp-based 5V regulators achieve better LR results, as you would expect, but not as good as the lower-current counterparts of Fig. 8a.

As with their operation unbypassed within the Fig. 8a circuit, the AD797 (b) and AD848 (c) in this 5V circuit show a LR of 70 or better within the audio band, with the AD848 appreciably better at high frequencies. The additional decoupling (d) and (e) improves LR above 100Hz for both devices, but not to quite the same degree as with the Fig. 8a circuit. Bypassing increases LR to 90dB in the audio band. Because of the greater potential for noise in a logic regulator, some type of raw supply filtering can be quite useful.

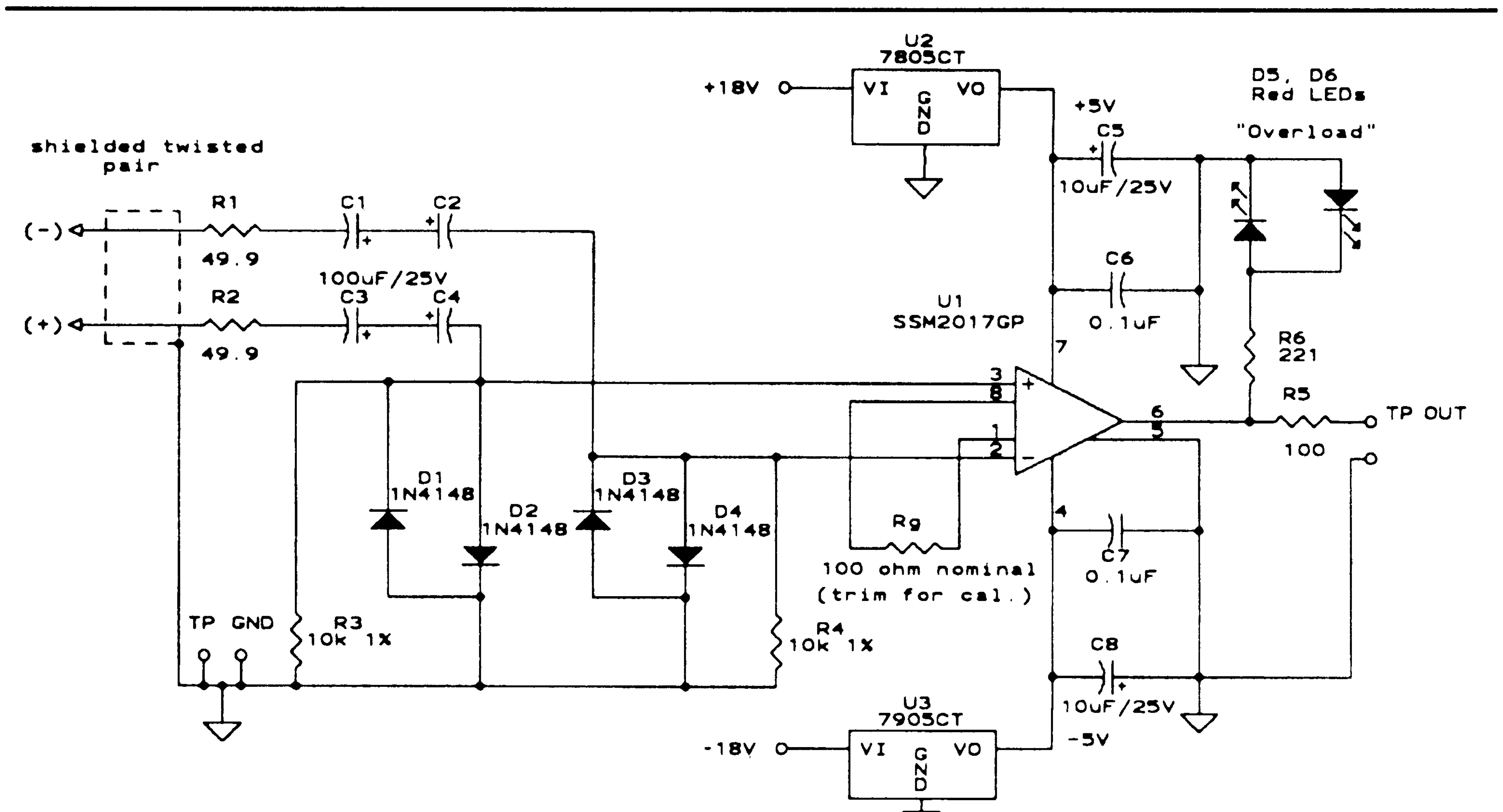

FIGURE 13a: Low-noise 100X balanced input preamp.

Noise Tests

Noise testing generally follows the scheme as applied to Fig. 2b. One of the keys to highly sensitive yet uncontaminated noise measurements is using low-

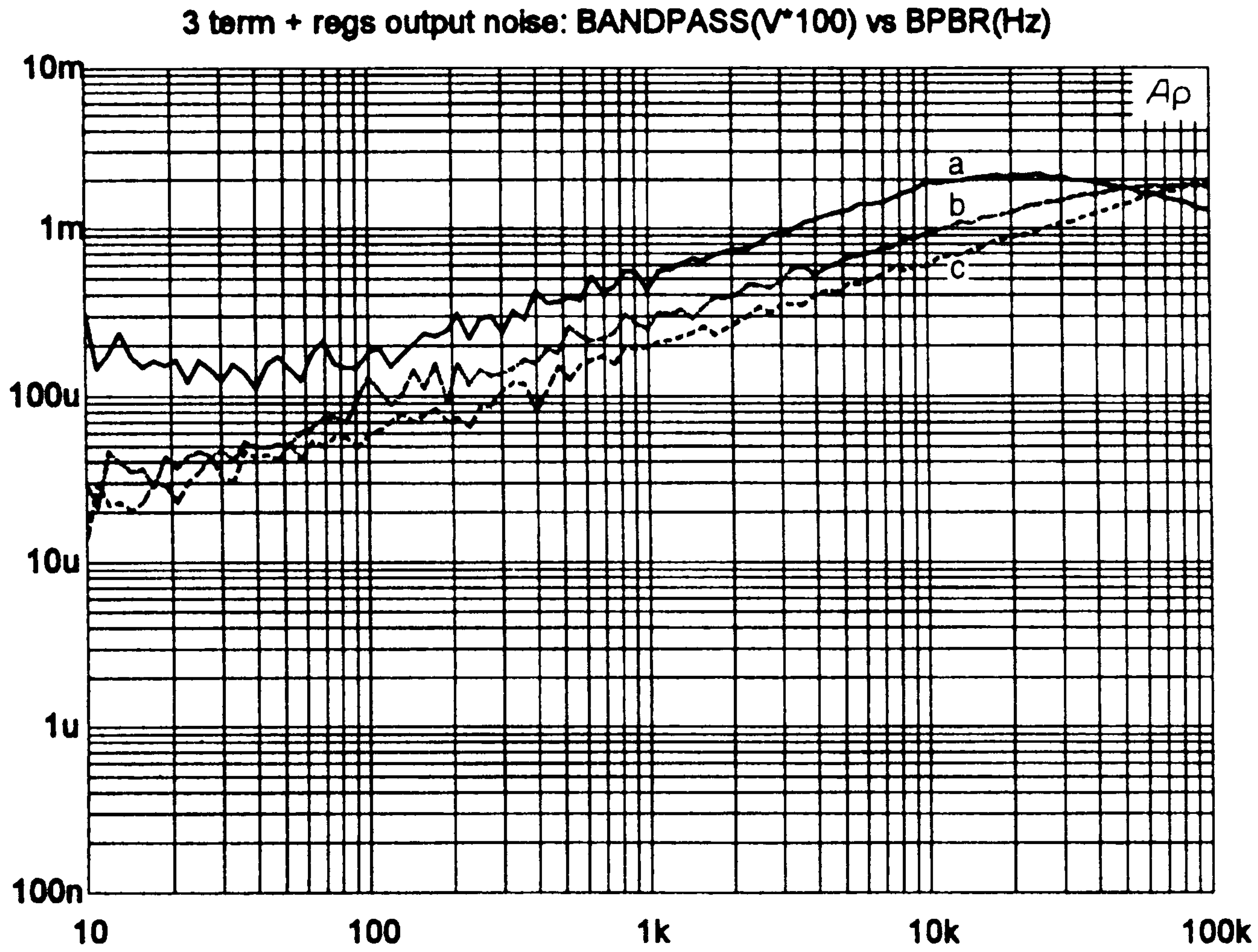

FIGURE 14a: Noise measurements for three-terminal positive regulators, a) 7815; b) 317; c) 1085.

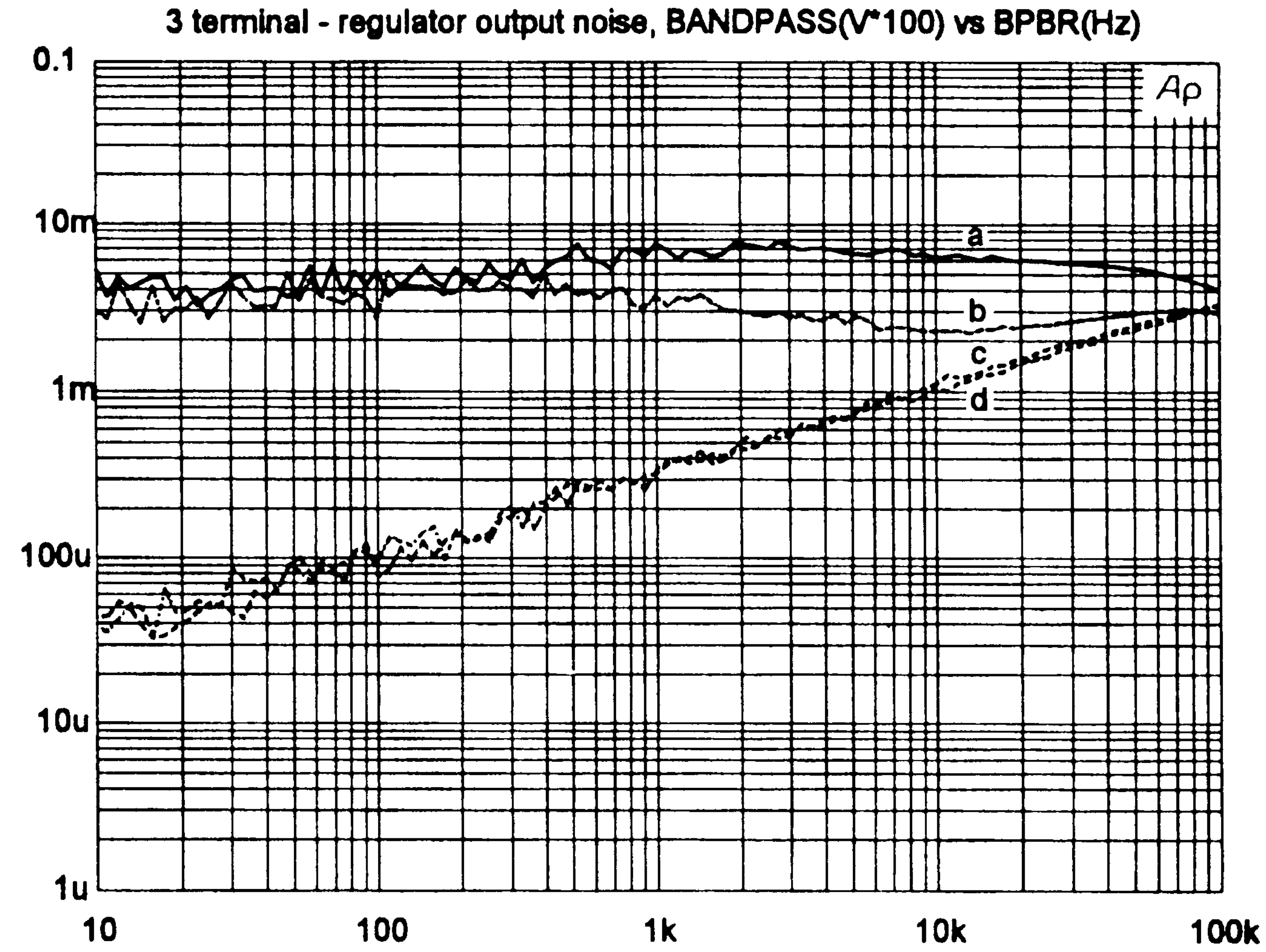

FIGURE 14b: Three-terminal negative regulator noise: 7915 samples—8818 (a) and 46AL (b); c) 337; d) 1033.

noise balanced preamplification. While the Audio Precision System One is a balanced input instrument, the sensitivity is not optimum for the lowest level measurements. These limits are pushed as the measured noise approaches noise densities of 10nV/√Hz or less, particularly at low frequencies. A gain of 100 balanced input preamp was developed specifically for this purpose (*Fig. 13a*).

The lower trace of *Fig. 13b* (b) shows the residual noise of this preamp (measured by the System One analyzer running "REG-NOI.TST"). In this test the analyzer's tracking bandpass filter sweeps over a range of frequencies, in this case 10Hz–100kHz, measuring the output in a narrow bandpass range. The filter for this function is a constant-Q type; thus, as the center frequency increases, the filter bandwidth increases.

As a result, a noise output which is spectrally flat measured through such a filter will appear to rise as frequency ascends, with a 3dB/octave slope. For example, for such a source, a noise density of 10nV/√Hz might be measured at 1kHz, 14nV/√Hz at 2kHz, and so forth. Some subsequent noise test examples illustrate this phenomenon.

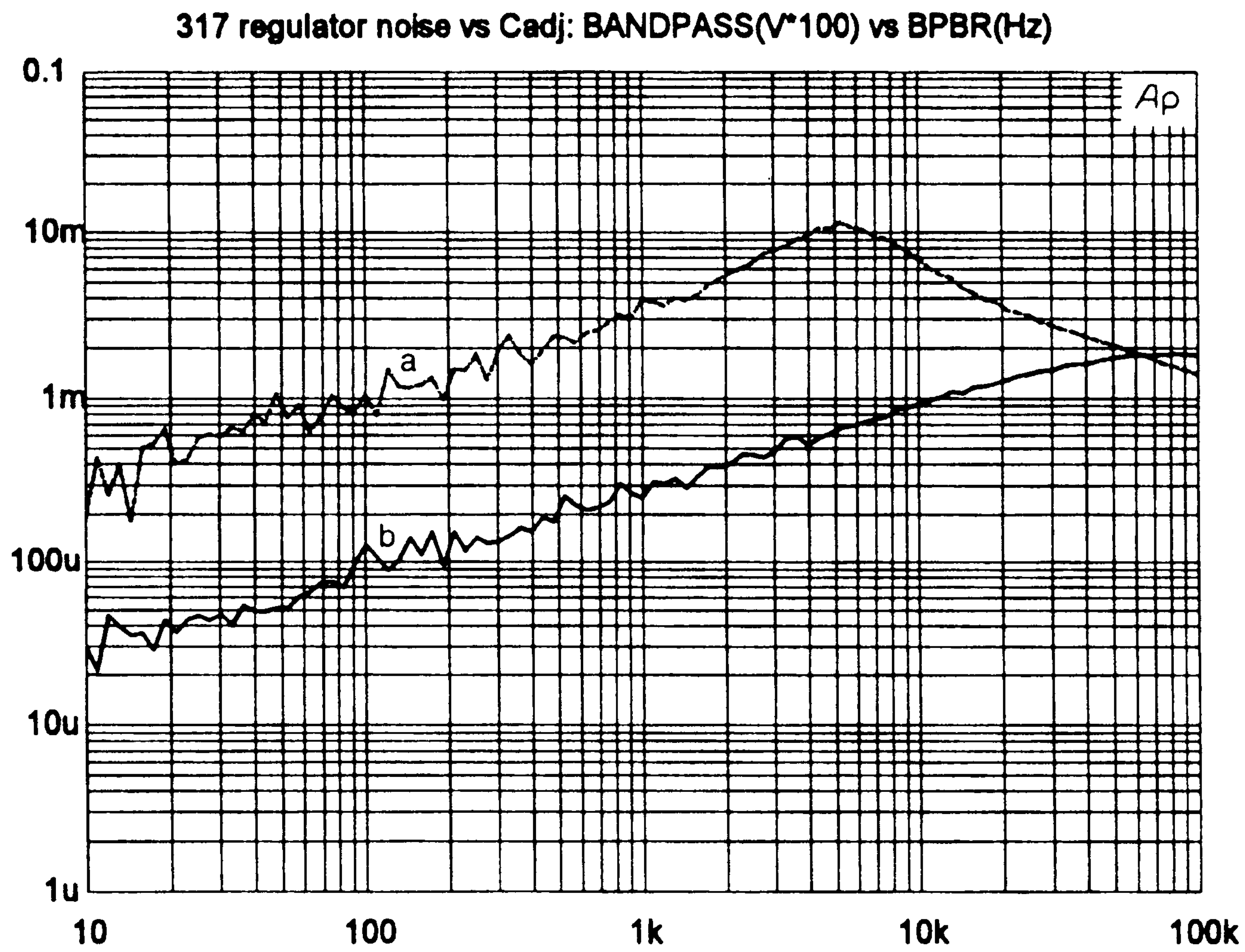

FIGURE 15: 317 regulator noise vs C_{ADJ}, a) C_{ADJ} = 0; b) C_{ADJ} = 100µF.

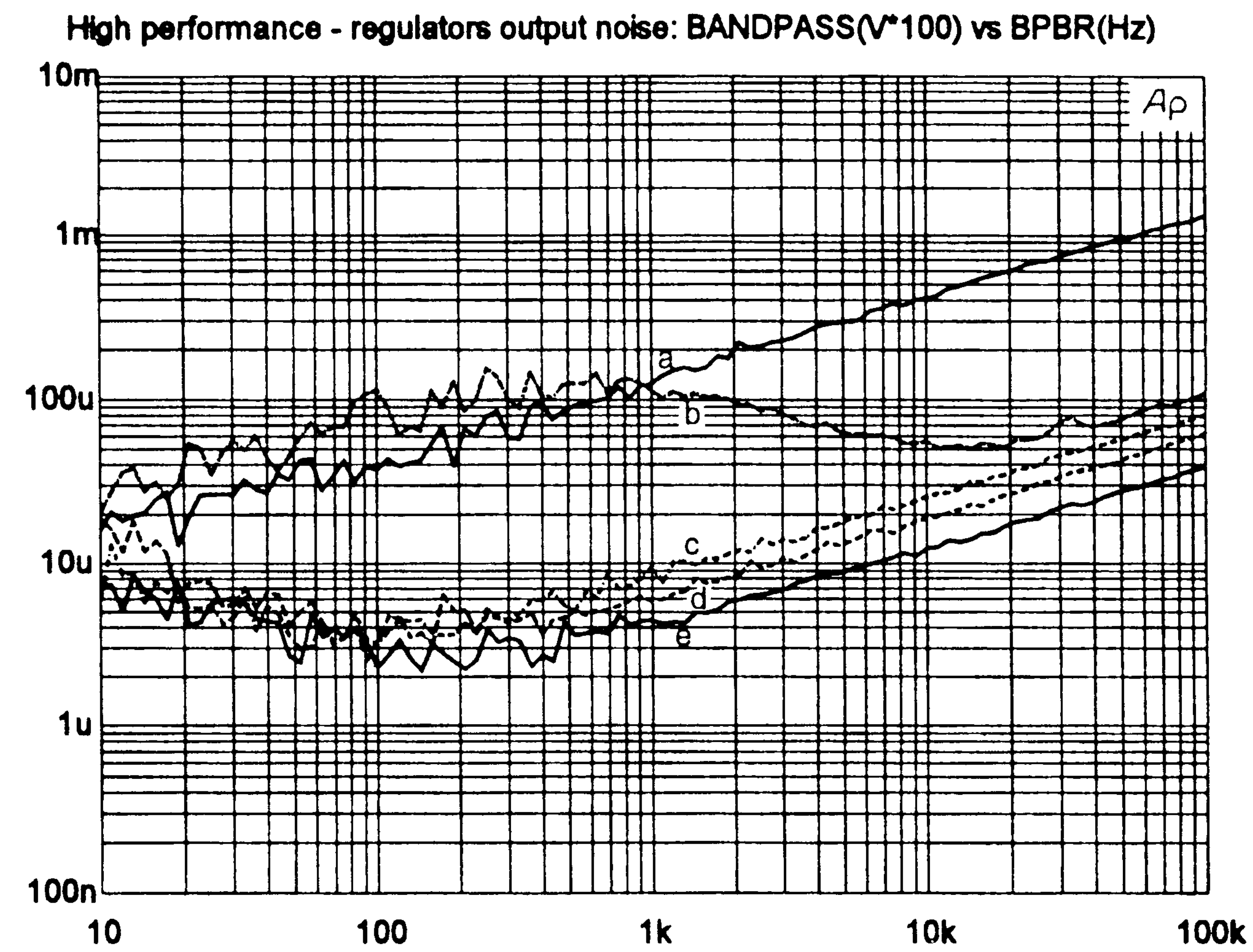

FIGURE 16a: High-performance negative regulator noise, a) unbypassed 329; b) POOGE 5.51 (Fig. 4); c) AD848 (Fig. 8b); d) Sulzer (Fig. 7b); e) AD797 (Fig. 8b).

In the *Fig. 13b* residual noise sweep including the X100 preamp (b), you can determine the equivalent input voltage noise density at a given frequency "F" by dividing the measured voltage by a factor of 100*√0.2316*F. (The factor of 0.2316 is based upon the bandpass filter noise bandwidth, which is a third-octave type.) You can simplify this divisor to approximately 48*√F. At 1kHz for example, the division factor is ≅1,518, at 100Hz it is 480, and at 10kHz it is 4,800. For the X100 preamp residual, the input referred noise at 1kHz is measured at 4µV/1,518 ≅ 2.6nV/√Hz.

For the analyzer-alone residual noise displayed in the upper trace (a), the as-measured noise data was scaled by exactly 100×, to keep the two traces on a similar display scale and allow direct comparison. As you can note, operating the preamp before the analyzer lowers the effective noise by a factor of 2–3× at 1kHz, and by higher factors at very low frequencies where the analyzer input noise rises.

Preamp Circuit

While it would be desirable to lower the preamp noise further, increasing the gain of the circuit raises the risk of dynamic range and saturation problems. The preamp IC, an SSM2017, is capable of noise levels down to 1nV/√Hz operating at gains of 1,000×. Here, at a gain of 100×, the typical equivalent SSM2017 input noise is on the order of 2nV √Hz, to which is added the noise of the input protection components. These nonideal (but necessary) parts raise the net overall noise to the measured level.

The preamp's noise rises gradually at low frequencies, as evident by the leveling of its trace. Above 1kHz the noise follows a roughly 3dB/octave rise, indicating the preamp noise is relatively flat at higher frequencies.

The *Fig. 13a* circuit includes back-to-back diodes across each of the two balanced inputs, which are necessary to prevent destruction of the SSM2017, as the inputs are connected directly to 15V outputs. R1-R2 limit the charging current to bipolar capacitors C1-C2 and C3-C4, as well as the clamp diodes, which allows safe direct jacking of the input to ±15V DC levels. The "Overload" back-to-back LEDs across the output light up when the DC output swings beyond ±1.5V, indicating possible nonlinear operation during the transient period as the input caps charge. When these LEDs extinguish, the output from U1 is in a linear range, so you can measure for noise.

You can facilitate accurate measurements by applying a known 1mV RMS level to the input of the preamp circuit, while monitoring the output for 100mV RMS. Calibration for various losses within the circuit is accomplished by trimming R_G, the SSM2017's gain set resistor, for a measured output of 100 ±0.5mV.

In measuring noise on regulators, the analyzer input is connected to the preamp TP OUT points. The regulator under test is probed directly with the shielded twisted pair input cable, which is connected to the regulator's TP OUT points (Fig. 2b). A noise analysis frequency sweep then produces a display similar to those of *Fig. 13b*, but in most cases higher in level, and often with one or more regions of complex frequency dependence. As you can see from the multiple decade log vertical scale of *Fig. 13b*, there is room for additional curves. The vertical scaling of 100nV to 10mV is maintained as consistently as possible in the following noise plots for ease of comparison between regulators.

Output Noise

In the noise results for the three-terminal positive regulator group (*Fig. 14a*), most units operate on an internal bandgap voltage reference, which is scaled upward from about 1.2V to the final output level. This amounts to a gain factor of about 12× in a 15V regulator. Accomplishing this scaling for DC only is sometimes difficult, that is, to *not* raise the AC noise components by the same factor.

As a result, three-terminal regulators can be quite noisy, especially if concern isn't taken in their selection and application. Among the various three-terminal regulators, lowest noise is generally realized with the adjustable types, *with the adjust pin bypassed* (as in these tests). The data below aptly demonstrates this point.

Using the 1kHz division factor of 1,518 with the positive regulator data of *Fig. 14a*, the measured noise is highest with the 7815 (a), at about 350nV/√Hz at 1kHz, while the 317 (b) and 1085 (c) measure about 180 and 130nV/√Hz at 1kHz, respectively. You'll notice some evidence of bandwidth limiting in the 7815, as the noise level falls off above 10kHz. This device's low-frequency noise also rises compared to the adjustable types, both of which maintain

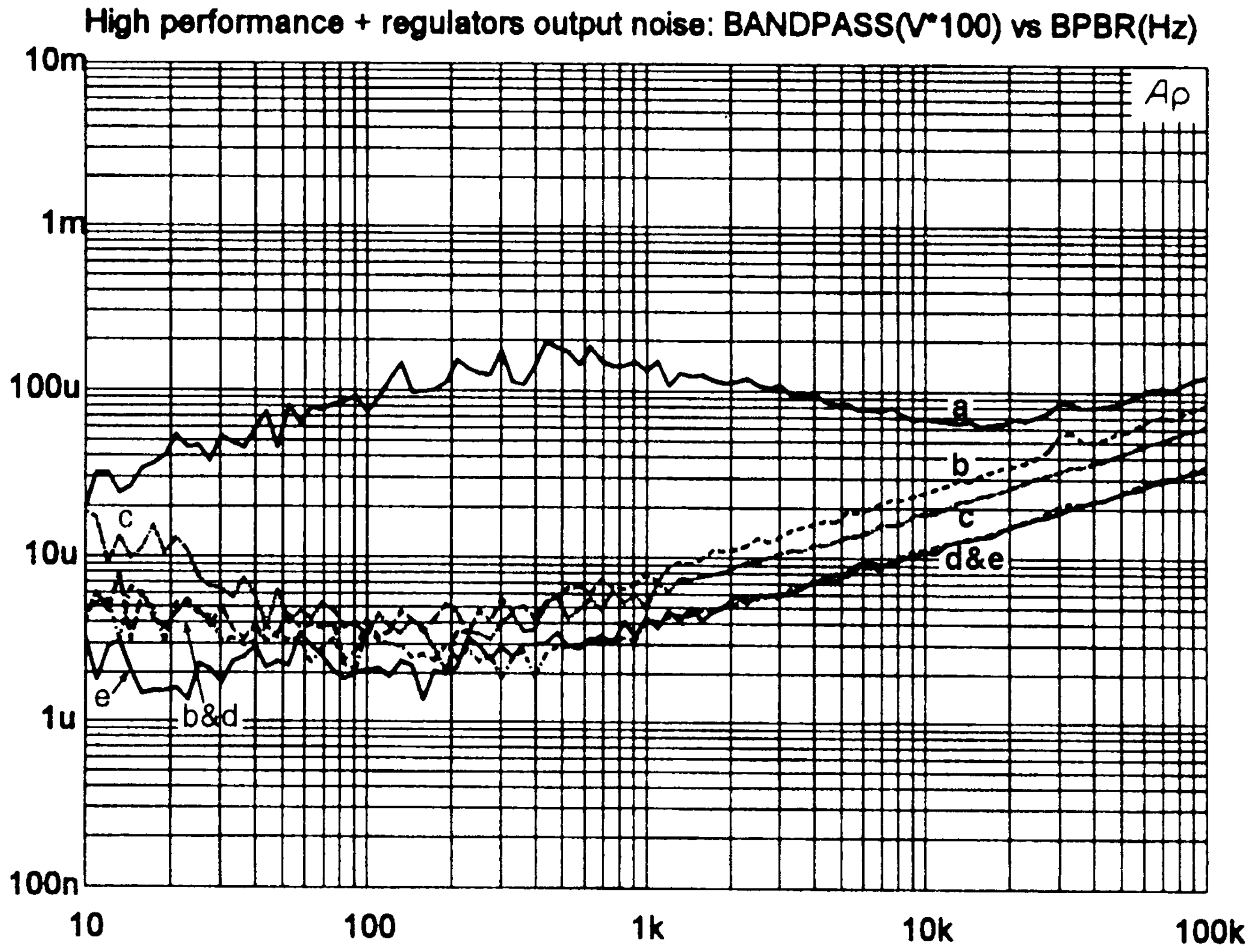

FIGURE 16b: High-performance positive regulator noise, a) POOGE 5.51 (Fig. 3); b) AD848 (Fig. 8a); c) Sulzer (Fig. 7a); d) AD797 (Fig. 8a); e) residual.

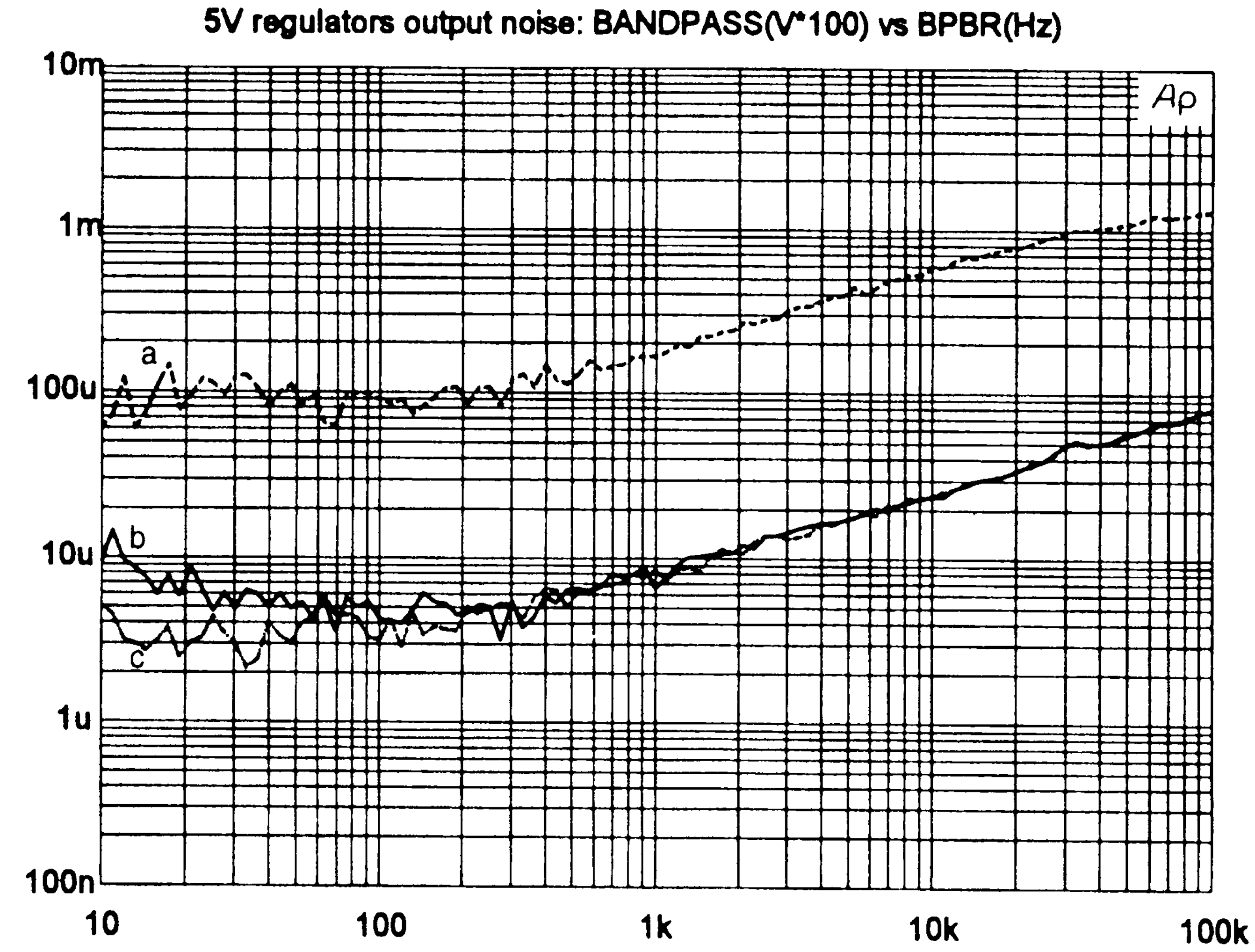

FIGURE 16c: 5V regulator noise, a) 7805CT; b) AD680 (Fig. 9); c) AD780 (Fig. 9).

a relatively constant 3dB/octave slope with frequency.

In the noise results of the negative group (*Fig. 14b*), the adjustable 337 (c) and 1033 (d) units have a similar 1kHz noise level of about 210nV/√Hz, while the two fixed output 7915 samples (a and b) show uncomfortably high 1kHz noise levels of about 4,600 and 2,300nV/√Hz. The two samples have different date codes, since the older initially measured unit (a) seemed to be unusually high. Noise in the (b) range for several 46AL date code samples seems to be typical, as does the 1/F noise characteristic. *Note that the scale of this plot ranges from 1μV to 0.1V.*

Figure 15 illustrates that adjustable three-terminal regulators with the adjustment pin bypassed offer lowest noise performance. These two plots measure the same 317 test regulator, both without (a) and with (b) the 100μF C_{ADJ} capacitor connected. The 1kHz noise levels are about 180 and 2,300nV/√Hz, respectively, roughly corresponding to the ≅12× AC gain dif-