# A comparative overview of power supply regulator designs with listening tests

*John Walton*


## Summary and Conclusion

Power supply regulation has been an "involved" and hotly debated topic of discussion for as far as I've been involved in the fields of amateur radio and audio, which means the early 1960's! While the merits of these devices can be illustrated quantitatively, the "listening impression" of the latest topology is always limited to comparison to what was just removed and replaced. The comparisons are often biased by the designer, vendor or tweaking audio experimenter who has invested money, time and perspiration in pursuit of perfection.

With this lack of objective comparison in mind, we set out to test 13 popular (or expensive) regulators both from the perspective of numeric analysis and through a controlled listening test. We measured each of the regulators for Line Rejection, Noise and Output Impedance and publish the data in this article. An all-day controlled listening test of the regulators was conducted by a subset of members of the New Jersey Audio Society and the impressions of various criteria including quietness, dynamics, and depth of soundstage tabulated and statistically analyzed.

What we found confirmed some, but not all of our biases. Most importantly, the listening test confirmed the need for subjective comparisons as the final arbiter of valid judgment. In short, the best sounding regulators were the Jung/Didden, Burson and Sjöstrom regulators. Only slightly inferior in performance, but still outstanding were the NewClassD, and the Linear Technology LT1963A/LT3015 devices. There was little "gross" correlation between the listening panel scores or ordinal rank of the devices when the entire group of 13 was examined. For the op-amp based devices however, line rejection and output impedance were seemingly the most important factors in producing a satisfying listening experience.


## Regulation

Simply put, inadequate power supply regulation degrades the listening experience by

1. Allowing hum, ripple, electro-magnetic interference ("EMI") and radio frequency interference ("RFI") to migrate through to speakers or headphones,

2. Injection of undesirable levels of noise into the system,
3. Distortion and oscillation in amplification circuitry caused by complex power supply impedance, or
4. Amplifier non-linearity owing to poor power supply rejection.
5. Amplifier non-linearity owing to interference from EMI or RFI

In his 1995 Audio Amateur article "Regulators for High-Performance Audio" in ref. 1 Walt Jung described test methodologies to analyze each of the three issues of 1) Line Rejection (or Power Supply Rejection Ratio, PSRR), 2) Noise and 3) Power Supply Impedance.

I thought it would be interesting to compare some of the newer regulator designs, commercial and "do-it-yourself" versions with those described in the Audio Amateur articles using the methodology employed by Jung. While the state of instrumentation is a bit better than it was in 1995, the technique and diligence exhibited by Jung in performing his measurements is of a higher order, particularly in regard to power supply output impedance.

It should be noted that power supply regulation of its own is often "necessary" but not "sufficient" in optimizing the listening experience. Attention to design, proper grounding and shielding techniques can play as important or more important role in providing a pleasing listening experience.

**Devices under Test**

The regulators tested for this article include the following:

1. Linear Technology LT1963A and LT3015 3-terminal regulators
2. Bybee "Music Rail"
3. Belleson SPL17 and SP79 "Super Regulators"
4. Jung/Didden Regulator with boot-strapped pre-regulation
5. Invisus (now discontinued)
6. Burson LM78A and LM79A
7. Sjöstrom Super Regulator
8. Sulzer Regulator
9. Salas Simple Shunt Regulator BIB
10. Pooge 5.51 Regulator
11. LM317/LM317 with bypassed Adjust pin
12. Super-Teddy Regulator
13. NewClassD Regulator

Of the above, the Bybee, Belleson, Invisus, Burson and NewClassD products are available as off-the-shelf items from distributors such as PartsConnexion and AudioCom International, (or directly from the manufacturer in the case of Belleson). The 3-terminal regulators should be in about every DIY audio enthusiast's parts bin, and are available at low cost throughout the world. The Jung/Didden, Sjöstrom, Salas and Super-Teddy Regulators were assembled on printed circuit boards available from various sources, while the Sulzer and Pooge 5.51 regulators were assembled on perf-board. Careful attention was paid to using the exact parts or those closely resembling the components used in the articles to describe the regulators, as well as original layout.

The Bybee "Music Rail" is not a "regulator" in any sense. As stated by the manufacturer, its purpose is to filter the power supply rails from unwanted noise and interference. This device has been critically acclaimed by many reviewers so we chose to include it, and see if 1) the manufacturer's data-based claims could be substantiated, and 2) what impression a listener experience if the device were inserted into the power supply chain.

## The Tests

**Equipment and Procedures:**

As Walt Jung has kept the original articles archived on his website (www.waltjung.org) it isn't necessary to completely rehash material previously stated in laborious detail. The test equipment used in preparation of this article appears in the Appendix.

Each of the devices under test ("DUT") was housed in its own aluminum chassis, and connection to the power source and load made with banana plugs and jacks. The boxes also "blind" the listening observations so that subjects cannot visually identify which regulator is used at any one time. Signal and measurement connections were made with shielded twisted pair and XLR connectors. The test setup is illustrated in photo 1.

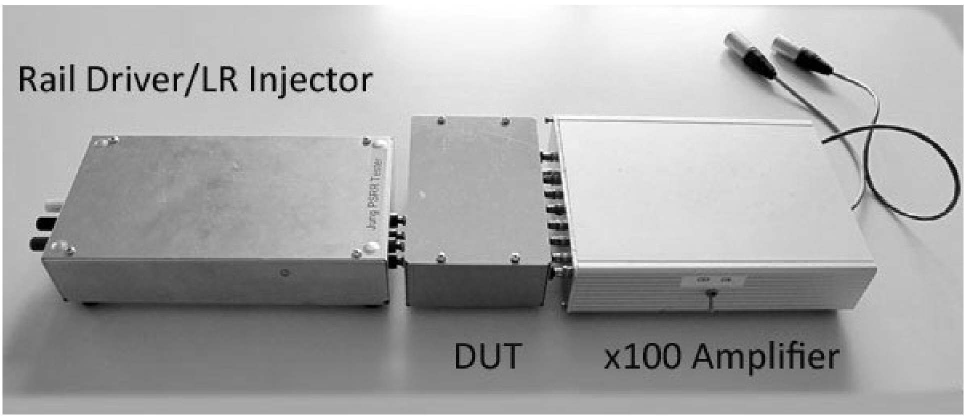


*Photo 1: Physical test setup.*

## Line Rejection (Power Supply Rejection Ratio)

LR/PSRR is measured by injecting a swept, 10Hz to 100kHz, 1 Volt peak sine-wave signal into the supply of the regulator, measuring the a.c. voltage on the output and converting to decibels.

$$LR = 20\log(ANLR_A \div ANLR_B)$$

To accommodate the pre-regulators of the “Improved” Jung/Didden design and the high current Sulzer regulator, the output was increased to 20.0 Volts.

The line rejection test setup is illustrated in **figure 1**.

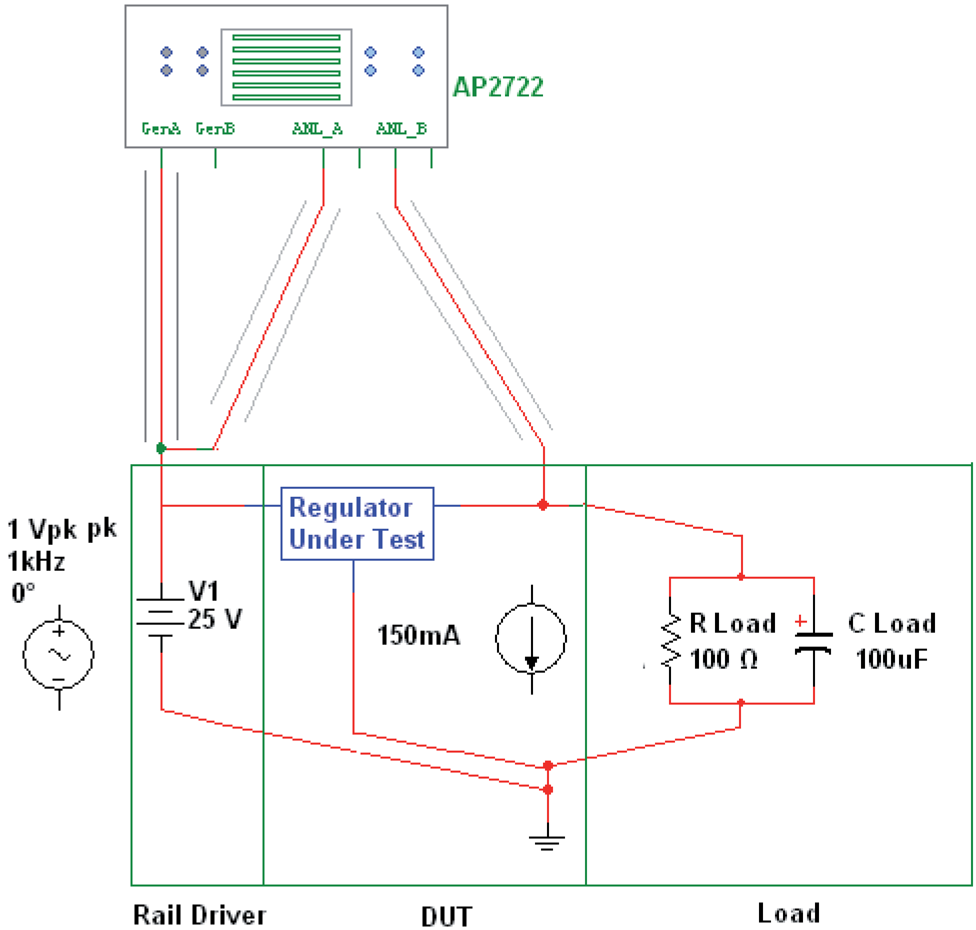


*Figure 1: Power Supply Line Rejection test setup.*

The 25 Volt DC source is, in actuality, the "rail driver" described by Jung in his articles, powered by the Tektronix PS5010 or HP 6271 supply. For the purpose of this experiment, a pair of positive and negative rail drivers was built into one aluminum chassis and the regulator "Device Under Test" connected to the rail driver via mating banana plugs and jacks. In like fashion, the regulator is connected to RLoad and CLoad which are housed in another separate chassis. Careful attention was paid to shielding and grounding, thus 60, 120, 180Hz line issues, "Pin 1 Issues", RFI and EMI are barely visible in the tests.

**Noise Measurement**

In the noise test, the power supply is replaced with a pair of sealed lead acid batteries. The Audio Precision SYS2722 is set up to operate in DSP Analyzer mode with 13th order bandpass filter engaged. Noise, measured as voltage per root hertz bandwidth, is found by applying the following equation:

$$Noise\left(\frac{V}{\sqrt{Hz}}\right) = V(Measured)/A \times \sqrt{Factor \times f}$$

Where "A" is the gain of the measurement amplifier and Factor is 0.2316 for the 3rd order filter in the SYS2722 Analogue Analyzer mode and 0.0539 in DSP 13th order mode. A macro written for the SYS2722 repeatedly samples the noise, calculates the RMS value and applies the equation above to chart noise per root Hertz at each frequency. No adjustment for the self-referenced noise of the SSM2019 amplifier, 0.9nV @1kHz, was necessary.

A second macro also tabulates the noise with A-Weighted, 20Hz-22kHz, CCIR-2K and CCIR-486 filters and appropriate detectors. The test setup is illustrated in **figure 2**.

The SSM2019 measurement amplifier used for these tests is shown in figure 3. It was built on a printed circuit board copper layer "Manhattan Style" and was powered with 9V alkaline batteries.

**Regulator Output Impedance**

Jung was able to measure regulator impedances in the low microOhms with his laboratory setup. Indeed, such a low threshold is necessary due to the very low impedance of the Jung/Didden Regulator when the AD797 is used. To put this in perspective, a length of #22 AWG hookup wire of 1.3-mil length has a D.C. resistance of 1 microOhm. The "Impedance Tester" is similar to a 4-wire impedance measurement apparatus (figure 4).

While not illustrated, connection between the regulator, current source and amplifiers was made with Mueller Kelvin clips. The blocking capacitor consists of two back-to-back 10mF capacitors for bipolar operation. As 50mA current flowing across one microOhm yields only 50nV, a SSM2019 balanced amplifier is used in a gain of 100x configuration to raise the low voltages well above the SYS2722 threshold. While this isn't absolutely necessary, a buffer does eliminate much of the complex impedance of the cabling between the meter and DUT. The second SSM2019 is used to meas-

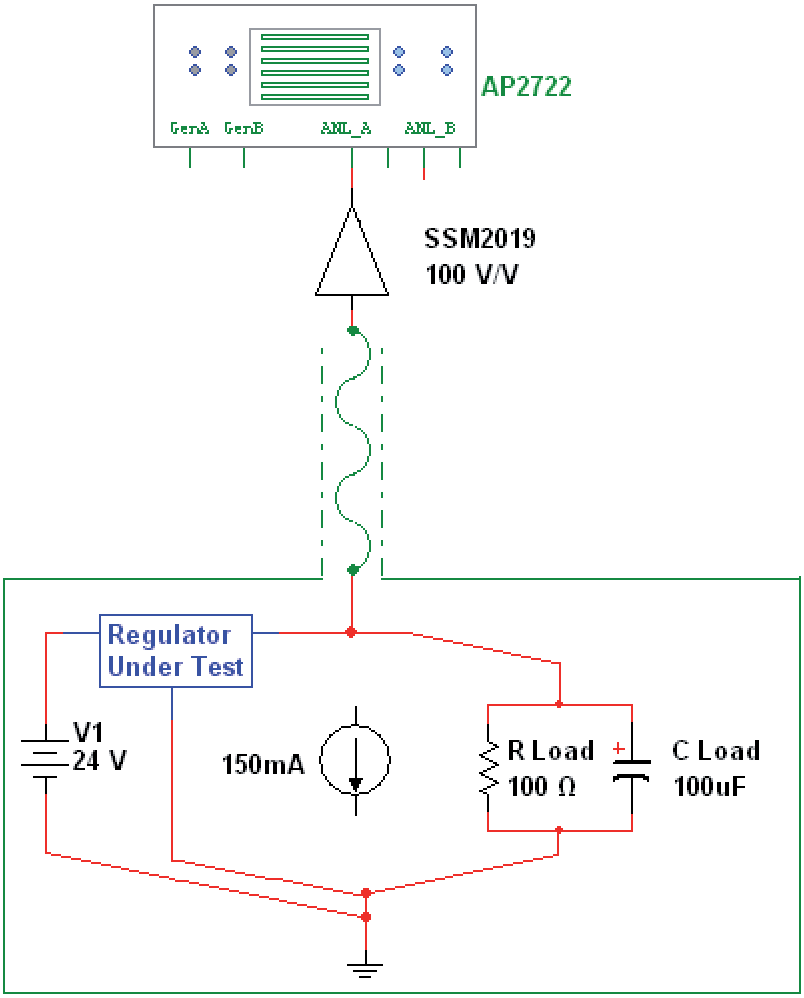


*Figure 2: Power Supply Output Noise measurement setup.*

ure the voltage drop across R1, eliminating the effects of the complex impedance of the cables and RFI protection of the SYS2722.

I wrote an APBasic Macro which establishes an Analog Generator "Equalization Curve" for each device in real time. The SYS2722 output at 10Hz and 100kHz is a bit low compared to 1kHz so the current is sampled at each point. As Jung points out in his article, moving the measurement probe only a few millimeters results in a significant change in measured impedance so where possible I probed each regulator board to find the point of lowest impedance. The macro is loosely based upon Tom Kite's Application Note for Audio Precision2 and is available on the Linear Audio website.

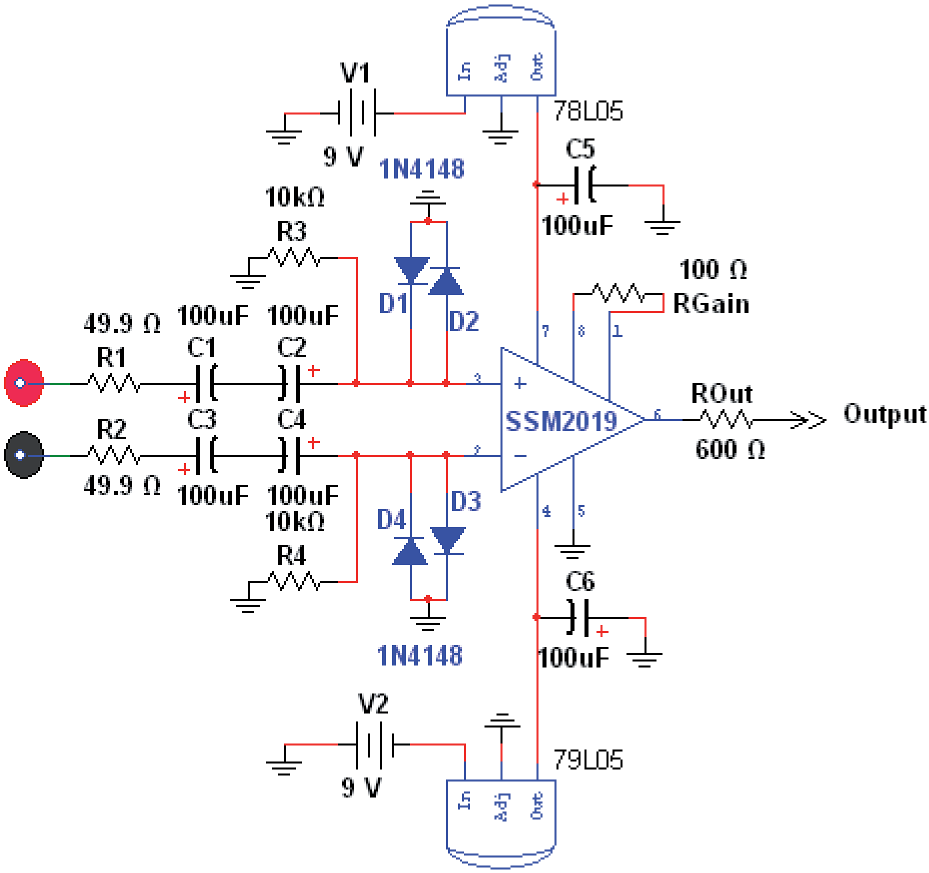


*Figure 3: Measurement amplifier.*

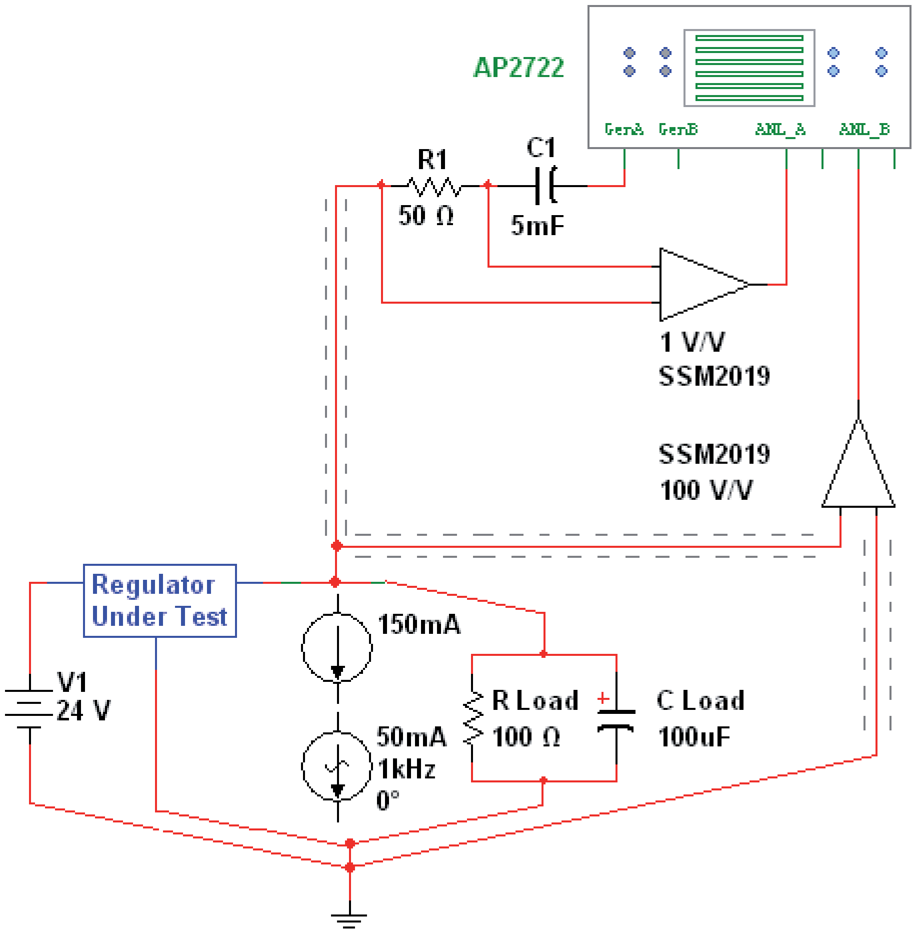


*Figure 4: Power Supply Output Impedance test setup.*

## The Data

### Line Rejection (Power Supply Rejection Ratio)

Line rejection measurements (**figure 5 and 6**) were generally consistent with those furnished by manufacturer data sheets and with those published by Jung in 1995. **Tables 1 and 2** rank the tested units for their 100Hz line rejection performance.

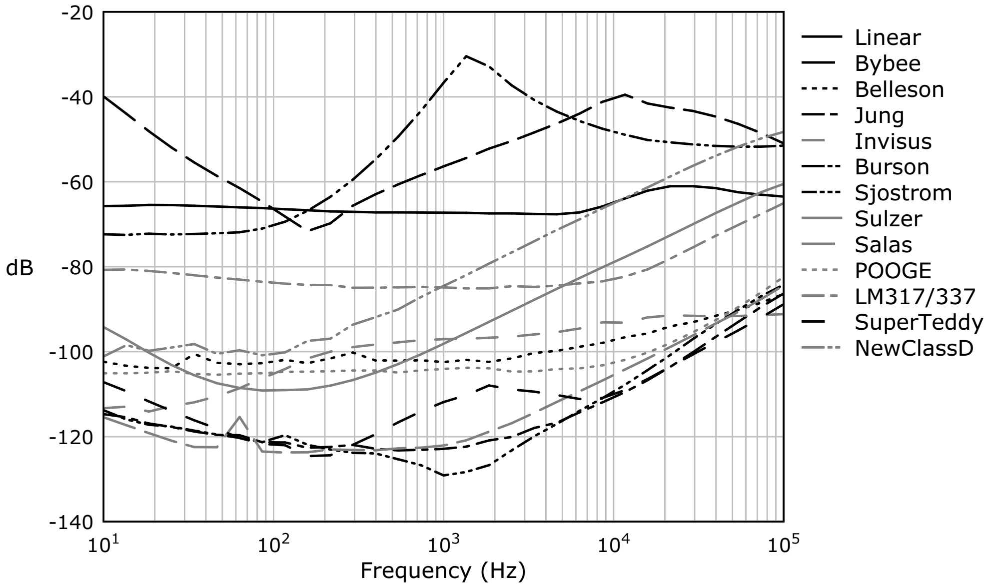


*Figure 5: Line rejection measurements for the positive regulators.*

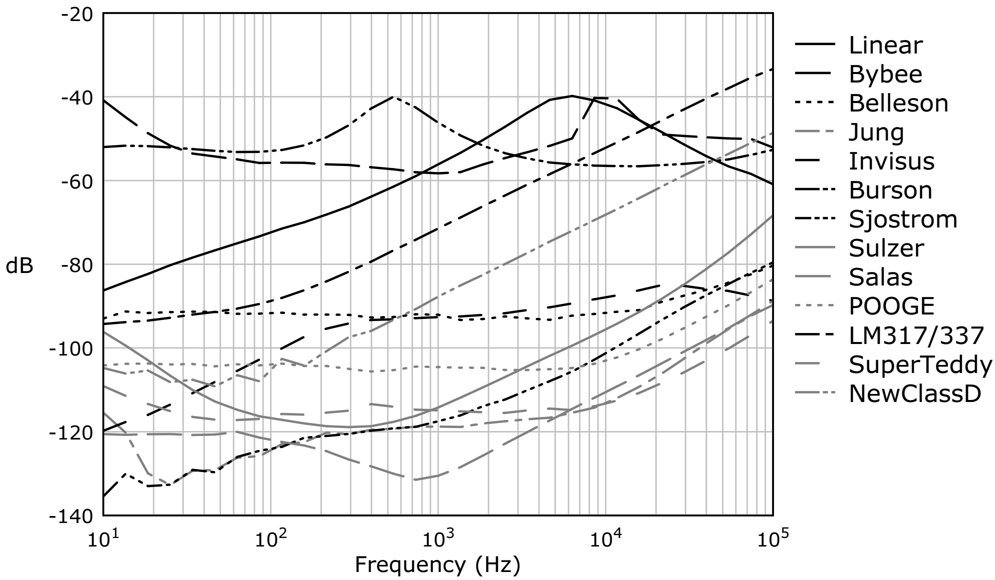


*Figure 6: Line rejection measurements for the negative regulators.*

| Device | 10Hz | 100Hz | 1kHz | 10kHz | 100kHz |
|---|---|---|---|---|---|
| Salas Simple Shunt | -115,4 | -123,7 | -122,1 | -104,2 | -84,4 |
| Super Teddy | -107,2 | -122 | -111,9 | -109 | -88,8 |
| Jung (AD825) | -114,7 | -121,4 | -122,9 | -109,5 | -86,3 |
| Sjöstrom | -113,8 | -119,7 | -129,1 | -107,8 | -84,3 |
| Sulzer | -94,2 | -109,1 | -98,1 | -77,7 | -60,5 |
| Pooge 5.51 | -105,1 | -104,7 | -104,1 | -101,9 | -82,4 |
| Invisus | -113,3 | -104,1 | -97 | -93,2 | -91,1 |
| Belleson | -102,4 | -101,9 | -102,4 | -96,6 | -86,4 |
| New Class D | -101,1 | -100,2 | -84,5 | -63,8 | -48,2 |
| LM317 | -80,7 | -84 | -84,8 | -82,3 | -65,1 |
| Burson | -72,4 | -69,4 | -36,7 | -48,9 | -51,5 |
| Bybee Music Rail | -39,9 | -68,1 | -56,4 | -39,5 | -51 |
| Linear LT1963A | -65,7 | -66,5 | -67,3 | -63,9 | -63,4 |

*Table 1: Positive Regulator Line rejection in dB ranked at 100Hz.*

| Device | 10Hz | 100Hz | 1kHz | 10kHz | 100kHz |
|---|---|---|---|---|---|
| Sjöstrom | -135,4 | -123,6 | -117,5 | -99,7 | -79,6 |
| Jung | -115,4 | -123 | -118,7 | -112 | -89,7 |
| Salas Simple Shunt | -120,6 | -122,4 | -130,5 | -109,2 | -88,7 |
| Sulzer | -96,1 | -117,2 | -114,2 | -94,2 | -68,3 |
| Super Teddy | -109,1 | -115,8 | -114,9 | -112,6 | -93,5 |
| POOGE 5.51 | -104,2 | -103,7 | -104,6 | -102,3 | -83,6 |
| New Class D | -104,8 | -102,6 | -87,7 | -66,9 | -48,6 |
| Invisus | -119,8 | -100,1 | -92,6 | -84,4 | 88,7 |
| Belleson | -92,9 | -91,6 | -92 | -91,4 | -80,3 |
| LM337 | -94,3 | -88 | -71,4 | -50,9 | -33,3 |
| Linear LT3014 | -86,3 | -71,4 | -56,1 | -42,7 | -60,9 |
| Bybee | -40,8 | -55,7 | -58,3 | -40,4 | -56,1 |
| Burson | -52 | -52,7 | -46,2 | -56,6 | -52,7 |

*Table 2: Negative Regulator Line rejection in dB ranked at 100Hz.*

**Output Noise**

Output noise was measured utilizing the SYS2722 Analyzer function with three of the built in filters. The regulators themselves were powered by sealed lead acid batteries. Each noise measurement was integrated over 0.5 seconds with 25 measurements taken. A single RMS value was calculated for each of the three filters, with the results shown in **tables 3 and 4** ranked for A-weighted RMS value.

| Device | 22-20kHz RMS | A-Weighted RMS | ITU486-3 Quasi Peak |
|---|---|---|---|
| ***Reference Amplifier*** | 0.34u | 0.22u | 1.13u |
| Super Teddy | 0.44u | 0.27u | 1.17u |
| Salas BIB | 6.21u | 0.34u | 1.53u |
| Jung LME49710 | 0.58u | 0.38u | 1.70u |
| Sulzer High Current | 0.76u | 0.46u | 2.08u |
| Jung AD797 | 0.86u | 0.48u | 1.70u |
| Jung AD825 | 5.12u | 2.02u | 9.13u |
| Invisus | 3.13u | 2.12u | 9.40u |
| Sjöstrom | 2.73u | 2.15u | 8.77u |
| Bybee Music Rail | 3.68u | 2.56u | 10.89u |
| POOGE 5.51 | 5.74u | 4.83u | 15.15u |
| LM317 Bypassed | 25.30u | 19.44u | 90.84u |
| Belleson SP17 | 55.14u | 37.36u | 156.0u |
| LT1963A | 74.41u | 57.31u | 269.0u |
| NewClass D | 81.94u | 63.28u | 289.4u |

*Table 3: Positive Regulator Output Noise Ranked by "A-Weighted" Noise.*

| Device | 22-20kHz RMS | A-Weighted RMS | ITU486-3 Quasi Peak |
|---|---|---|---|
| ***Reference Amplifier*** | 0.34u | 0.22u | 1.13u |
| Super Teddy | 0.52u | 0.28u | 1.24u |
| Jung AD797 | 0.53u | 0.28u | 1.21u |
| Salas Simple Shunt | 4.17u | 0.39u | 1.45u |
| Bybee Music Rail | 2.14u | 1.59u | 6.56u |
| Invisus | 3.15u | 2.13u | 9.37u |
| Sulzer High Current | 1.88u | 2.18u | NM |
| Sjöstrom | 1.88u | 2.30u | 10.79u |
| Jung AD825 | 3.28u | 2.60u | 12.57u |
| POOGE 5.51 | 6.52u | 4.92u | 14.57u |
| LM337 Bypassed | 30.4u | 24.4u | 111.2u |
| NewClassD | 90.2u | 65.6u | 298.3u |
| Belleson | 98.7u | 77.6u | 366.5u |
| Burson | 122.8u | 99.0u | 163.4u |
| LT3015 | 219.5u | 214.4u | 1053u |

*Table 4: Negative Regulator Output Noise Ranked by "A-Weighted" Noise.*

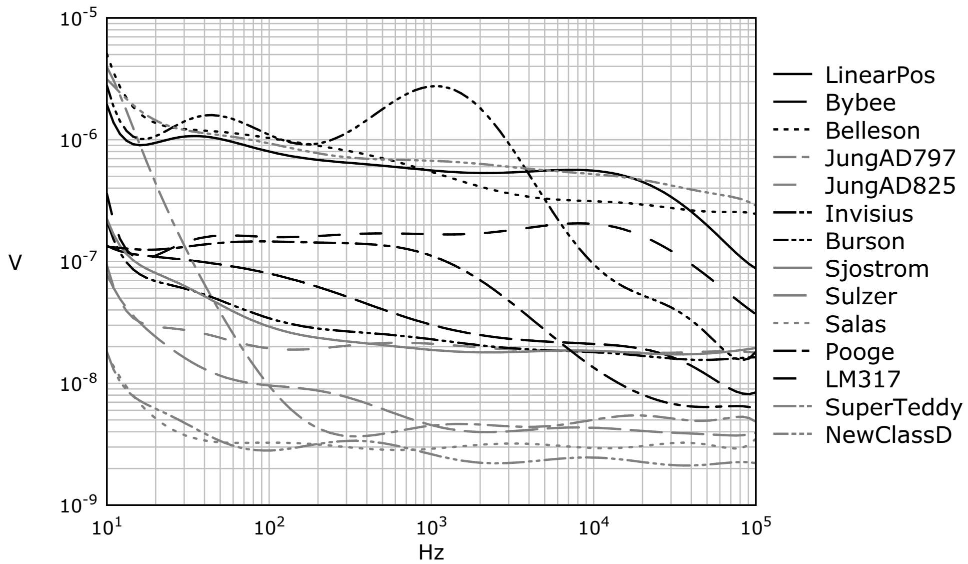


*Figure 7: Positive Regulator Output Noise, computed as voltage per root Hertz.*

| **Device** | **10Hz** | **100Hz** | **1kHz** | **10kHz** | **100kHz** |
|---|---|---|---|---|---|
| Jung/Didden (AD797) | 14.1u | 14.9u | 79.8u | 725.5u | 7.59m |
| Jung/Didden (AD825) | 114.5u | 82.83u | 134.8u | 1.07m | 11.30m |
| Sjöstrom (AD825) | 148.2u | 147.2u | 142.1u | 448.9u | 6.31m |
| Invisus | 512.3u | 466.3u | 484.4u | 1.083m | 9.59m |
| Sulzer (High Current) | 1.50m | 1.29m | 1.37m | 3.81m | 15.63m |
| Salas BIB (MOSFET) | 2.09m | 1.98m | 1.75m | 3.13m | 26.07m |
| POOGE 5.51 | 2.46m | 2.48m | 2.61m | 2.61m | 3.99m |
| LM317 + 100uF Bypass | 2.50m | 2.93m | 5.13m | 56.22m | 142.9m |
| NewClass D | 4.44m | 4.32m | 4.50m | 13.08m | 90.24m |
| LT1963A (Remote Sense) | 8.50m | 5.60m | 4.20m | 45.93m | 79.50m |
| Belleson (SP*17) | 14.55m | 14.56m | 10.63m | 9.13m | 17.32m |
| Burson | 184.3m | 177.4m | 528.0m | 120.3m | 81.05m |
| Super Teddy | 415.2m | 424.2m | 401.0m | 157.1m | 93.26m |
| SPECIAL CASE | | | | | |
| Bybee Music Rail | 59.85m | 3.80m | 5.18m | 31.93m | 119.2m |

*Table 5: Positive Regulator Output Impedance (ohms).*

Adjusting for the self-referred noise of the SSM2019 100x amplifier, it is apparent that several devices contribute virtually no additional noise. The measurement of noise characteristic of the regulators is consistent with those illustrated by Jung. **Figure 7** illustrates the difference in noise measurements for positive rail regulators, computed as voltage per root Hertz.

### Output Impedance

As mentioned, output impedance is the most difficult of the three tests. Each regulator was probed to determine the Low Zo node which was usually the emitter lead of the output pass transistor. In rank order (100Hz), the results are shown in **table 5** (positive regulator) and table 6 (negative regulator).

As our "sanity test" we compared the results in table 5 to those published by Jung in Audio Amateur 2/95 and by Didden in 3/95, as well as analysis of 0.100 Ohm resistors and inductors and capacitors of various values. While the results of the AD797 Jung/Didden regulator compares well with those in Didden's 3/95 article, they are slightly worse than those shown by Jung in his lab test for the device in 2/95. The data for the bypassed LM317 and the POOGE 5.51 regulators we obtained closely correspond to those published by Jung and Didden. (The Jung/Didden regulator in this test was the "improved" version with pre-regulation and with AD797AN or AD825AR amplifier.) The AD797AN was used in both the original and improved versions of the Jung/Didden design and differences in impedance in the micro-Ohm region may owe to slightly inferior probing technique. The output impedance versus frequency is shown in **figures 8 and 9**.

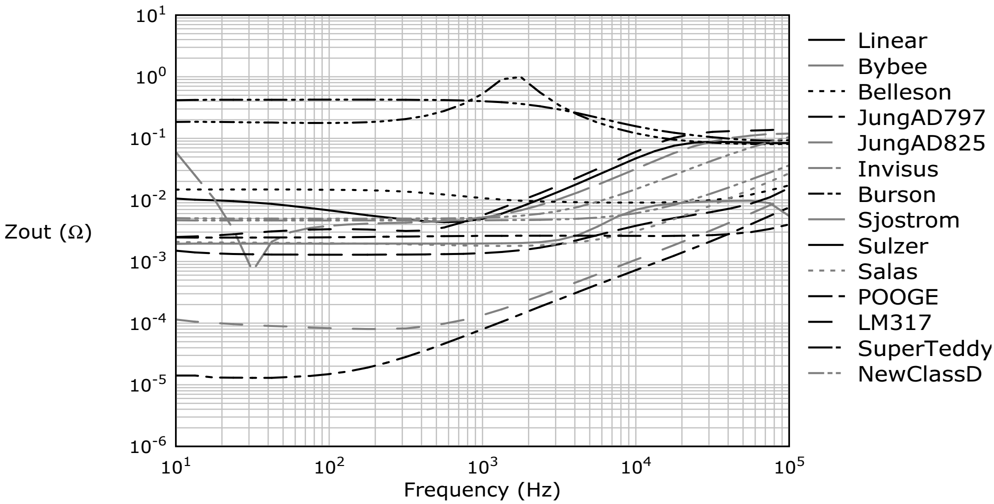


*Figure 8: Positive regulator Output Impedance versus Frequency.*

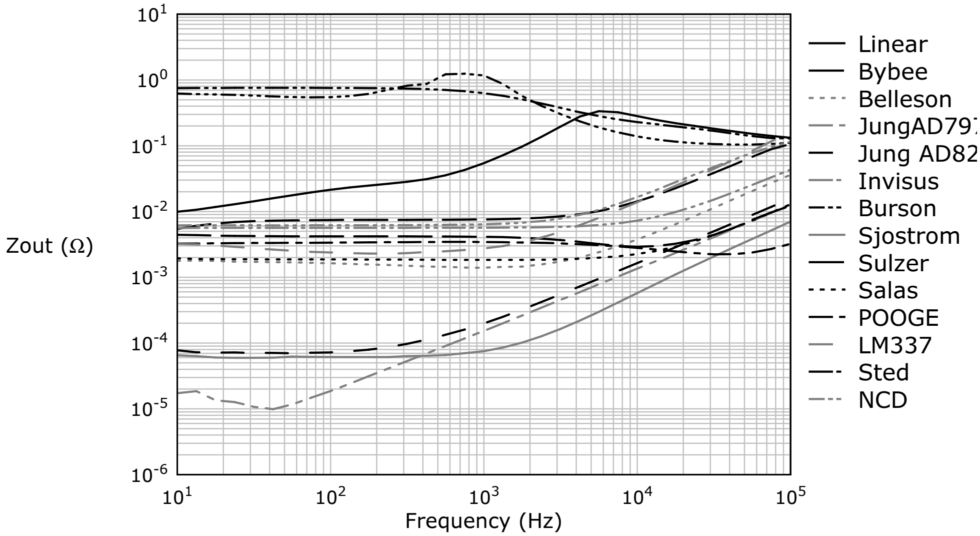


*Figure 9: Negative regulator Output Impedance versus Frequency.*

We were disappointed that we were unable to replicate Jung's results for the Sulzer regulator. It may be that the pass transistor utilized in the 2012 tests is significantly different than those deployed by Sulzer or that a faster opamp than the NE5534 had been used for his tests.

| **Device** | **10Hz** | **100Hz** | **1kHz** | **10kHz** | **100kHz** |
|---|---|---|---|---|---|
| Jung/Didden (AD797) | 17.3u | 18.6u | 153.3u | 1.35m | 12.76m |
| Jung/Didden (AD825) | 77.1u | 72.0u | 199.4u | 1.643m | 15.83m |
| Sjöstrom (AD825) | 283.1u | 73.2u | 116.2u | 1.04m | 1.06m |
| Invisus | 255.9u | 356.0u | 395.1u | 1.25m | 11.18m |
| Belleson (SPJ) | 622.5u | 502.5u | 675.7u | 4.21m | 42.16m |
| Salas BIB (MOSFET) | 1.57m | 1.50m | 1.52m | 2.85m | 21.77m |
| LM337 + 100uF Bypass | 2.36m | 1.71m | 2.17m | 13.13m | 151.4m |
| POOGE 5.51 | 2.64m | 2.71m | 2.86m | 2.86m | 2.86m |
| Sulzer (High Current) | 4.44m | 4.18m | 4.11m | 2.92m | 12.7m |
| NewClass D | 6.13m | 6.17m | 6.39m | 16.52m | 115.0m |
| LT1963A (Remote Sense) | 9.95m | 21.41m | 54.40m | 281.9m | 132.2m |
| Burson | 620.8m | 546.6m | 1171m | 138.4m | 110.7m |
| Super Teddy | 627.4m | 642.5m | 549.5m | 234.1m | 145.1m |
| SPECIAL CASE | | | | | |
| Bybee Music Rail | 51.27m | 7.18m | 7.64m | 13.78m | 101.5m |

*Table 6: Negative Regulator Output Impedance (ohms).*

With respect to the Belleson regulators, it should be noted that the graph on the company's website is for their SPJ series of regulators, and that operating conditions used in our tests differ from those used by Belleson. We were able to validate the manufacturer's claims for the negative version of the Belleson SPJ regulator which is a lower peak current device.

Results for the negative rail regulators appear in **table 6**.

**Listening Tests**

A panel of enthusiasts from the New Jersey Audio Society served as guinea pigs for our listening test. The NJAS meets monthly at members' homes, audio dealers or other venues to compare equipment and recordings.

The setup consisted of a Sony XA5400ES SACD player, four of the Borbely "All FET" Line Amplifiers [3], a stock Pass Aleph 5 amplifier and Pioneer-TAD S3-ex loudspeakers. Kimber-cable was used for the interconnects and Radio Shack "flat" for speaker cabling. A K-works Power- Station supply conditioner and Empowered V24 cables were used to connect the power player and line amplifier to the power conditioner.

Stuart Yaniger suggested that we forsake the trendy, high performance audio operational amplifiers like the OPA637 or LME49720 and choose a line amplifier with more humble power supply performance. The Borbely "All FET", in its complementary fashion (**figure 10**; see also Figure 5 in the audioXpress article) fits this bill. It is extremely low noise and THD% is excellent. PSRR, however, is comparatively poor at -40dB at 1kHz. Compare this to audio operational amplifiers with PSRR of -90dB or better. The Borbely line amplifiers were modified in one small respect in that the +/- 24 VDC he had used is above the rail voltages used for these tests. The lower supply voltage means that the higher level distortion will be somewhat greater than the figures indicated in Borbely's article, and indeed, at 3 VRMS output THD+N% was 0.010% versus the 0.0055% he reported. At lower output levels, however, the distortion was less than 0.001%. The gain of each amplifier was set to 20.0dB with a small trimpot and DC offset nulled to near 0mV. The input and output devices were matched for Idss of 7.0mA for the input stage and 10.8mA for the output stage. The test amplifier and an accompanying headphone amplifier draw approximately 60mA in use.

After listening to several sample recordings, Track 3 of Rachmaninoff Symphonic Dances, Funeral March, "Andante con moto (tempo di valse)" from Reference Recordings5 was chosen for the test. This recording has very good demonstration of percussive, string and brass instruments, quiet passages and moments of bombastic attack!

Each panelist was given a ballot with the device number, and space for recording their impressions. The rankings were determined by scoring each device for Dynamics, Quietness and Noise, Renders Complex Passages, Size of Soundstage and Inner Detail, and Overall Impression. These are the factors

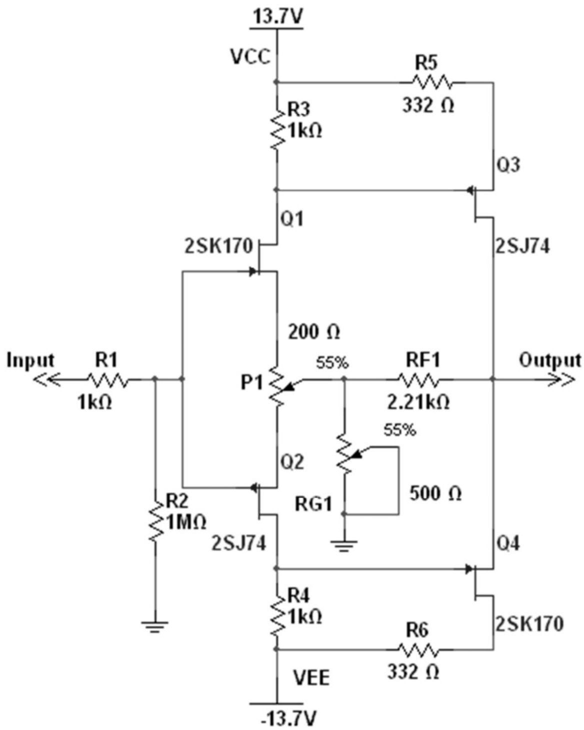


*Figure 10: Borbely All-FET line amp used as test load.*

which appear as criteria in audiophile magazines. A "5" was accorded for "excellent" and a "0" for "poor". All of the regulators were reviewed one time for a general impression and familiarisation, and then reviewed again for criticism. The regulators were then segregated into 3 groups and the best (including ties) were re-examined. The listening test was completed over a period of 7 hours.

## Results

In the first set of listening tests, the winner by a nose, was the Jung/Didden regulator, first discussed in the 1/1995 issue of The Audio Amateur and updated to include the changes suggested in AudioXpress 5/00. Following closely behind were the Burson Regulator from Australia and the Sjöstrom from Sweden. A second group which was deemed slightly inferior consisted of the Linear Technology LT1963A/LT3015 devices and the "NewClassD" regulator. At the bottom of the list were the Bybee Music Rail, the Salas Simple Shunt and Invisus. **Table 7** lists the overall ranking.

After the first round the best sounding of the lot (Jung/Didden, Burson, Sjöstrom, Linear and New Class D) were separated for another round of critical listening. At this time, no scores had been tabulated so there was no bias applied to the rankings. In the second series with a smaller field, the Sjöstrom was rated #2 and the Burson #3.

| Device | Rank | Score | Comments |
|---|---|---|---|
| Jung/Didden | 1 | 4.00 | Best overall, very well behaved best sound-staging, great balance, good top end, among the very best |
| Burson | 2 | 3.92 | Socko Dynamics, Black Background, Engaging timbre and attack, emotionally appealing, "Oh Yeah", good definition everywhere, top contender. "Torn between this one and #4" (Jung/Didden) |
| Sjöstrom | 3 | 3.73 | Good tonality, control, very quiet, best microtones, superb inner detail, most authentic, nice overall balance and tone. |
| Linear Tech LT1963A/LT3015 | 4 | 3.60 | Good height, clearest top end. |
| NewClassD | 5 | 3.57 | Excellent plummy and detailed, feeling of well crafted soundstage |
| Sulzer | 6 | 3.00 | Good and quick, but imperfect in details, inner detail slightly awash, tambourine smeared, tuneful bass end, some weirdness to textures. |
| POOGE 5.51 | 7 | 2.80 | Top end a bit recessed, clean, neutral moderately quick, a bit soft on transients but insufficient in micro details. |
| LM317/337 | 8 | 2.47 | Weak bottom control, dull, a yawner, and unremarkable, bass bloom. |
| Belleson | 9 | 2.40 | Dull and uninvolving, top end not right, poor control, upper strings congested. |
| Super Teddy | 10 | 2.14 | Not pleasant, seemed to generate 3rd harmonics, average top end, veiled, buried localization, congested. |
| Bybee Music Rail | 11 | 1.78 | Flabby bass |
| Salas Simple Shunt | 12 | 1.43 | Slightly coarse, not engaging, competent but uninteresting, not well coordinated, somewhat murky. |
| Invisus | 13 | 1.33 | Slow transients, not a winner, congested yet interesting soundstage, exceptionally quiet, some harshness in complex passages. |

*Table 7: Overall listening test score ranking.*

I placed myself in the position as impartial referee for the tests as I was aware which devices were hidden behind their aluminum chassis. My only comment after the test was that the top 5 devices as a cohort sounded much better than the bottom 6. The 2 devices in the middle were clearly better than the bottom 6, but not in the same league as the top 5!

**What makes a great regulator?**

We reviewed the scores of the test with the listening panel to confirm that they were, indeed, correspondent to their listening impressions since they are highly subjective. It should be noted that the listening tests were conducted with equipment which is not typical of the average audiophile listener, particularly the Borbely Line Amplifier which readily demonstrates power supply issues, and for which even-order harmonics dominate giving it a pleasing but tube-like quality.

Firstly, when the Burson device was first tested, I was dubious about its prospects in front of our highly critical listening panel. When one looks at the plot of impedance and line rejection it isn't the prettiest of the class. We will venture a guess that the PSRR and impedance hump, occurring as they do in the critical "presence" region, allows instrumental dynamics to appear better than they actually are. Horses for courses, there may be a reason that there was a presence control knob in your 1970's Yamaha receiver.

Secondly, the measurements of Linear Tech devices are typical of low dropout regulators and we did not expect them to yield the listening performance scores which were attained. Linear states in their data sheets, however, that they have a fast transient response. We think that their performance was enhanced by utilizing a "remote sense" option which militates against parasitic inductance and resistance. Tantalum capacitors, as specified in the LT1963A and LT3015 datasheets were used with generic Vishay/BC Component metal film resistors.

To examine whether there was any correlation between the listening impressions and the quantitative measurements we regressed the data and scores at decade intervals of frequency. We were skeptical that the regression analysis would show any meaningful correlation, and a cursory examination of the data would indicate very little correlation.

Using Microsoft's Data Analysis "Regression Tool" I conducted several analyses of the data calculating the correlation coefficient to the subjective scores from Table 7, to measures of Line Rejection, Noise and Output Impedance as independent variables. The regression analyses were run for 5 frequencies from 10Hz to 100kHz and the results tabulated. The regression analysis was performed again with the ordinal rank of the device used as the dependent variable. As the tables below indicate, for the most part the only conclusion one could derive is that listening performance is weakly related to line rejection at high frequencies.

In order to tease out some relationship which might have some, albeit low, statistical merit, we reduced the analysis to those regulators which were opamp based, including the Jung/Didden, Sjöstrom, Sulzer, New Class D, Linear Technology and Fairchild (LM317/LM337) devices. Given the low number of samples, low correlation coefficients were anticipated. **Tables 8a through 8f** show the correlation data.

It is apparent that in **this** family of regulators, in this **test** situation in which the source is not a low output moving coil cartridge, noise is of little importance to the rankings. Allowing for the small number of samples, line rejection seems to be most important particularly for subsonic and supersonic artifacts.

| Frequency | R^2 to Score | R^ to Rank |
|---|---|---|
| 10 | 0,25 | 0,289 |
| 116 | 0,159 | 0,212 |
| 1000 | 0,186 | 0,35 |
| 11660 | 0,121 | 0,359 |
| 100000 | 0,189 | 0,494 |

*Table 8a: Line Rejection Ratio Correlation – Positive Op Amp Based Regulators.*

| Frequency | R^2 to Score | R^ to Rank |
|---|---|---|
| 10 | 0 | 0,381 |
| 116 | 0,067 | 0,17 |
| 1000 | 0,13 | 0,186 |
| 11660 | 0,224 | 0,317 |
| 100000 | 0,591 | 0,729 |

*Table 8b: Line Rejection Ratio Correlation – Positive Op Amp Based Regulators.*

| Frequency | R^2 to Score | R^ to Rank |
|---|---|---|
| 10 | 0,062 | 0,001 |
| 116 | 0,029 | 0,006 |
| 1000 | 0 | 0 |
| 10000 | 0 | 0 |
| 100000 | 0 | 0 |

*Table 8c: Noise Bandwidth Correlation – Positive Op Amp Based Regulators.*

| Frequency | R^2 to Score | R^ to Rank |
|---|---|---|
| 10 | 0,002 | 0,018 |
| 100 | 0,034 | 0 |
| 1000 | 0,027 | 0,002 |
| 10000 | 0,006 | 0,001 |
| 100000 | 0 | 0 |

*Table 8d: Noise Bandwidth Correlation – Negative Op Amp Based Regulators.*

| Frequency | R^2 to Score | R^ to Rank |
|---|---|---|
| 10 | 0,082 | 0,227 |
| 100 | 0,002 | 0,34 |
| 1000 | 0,001 | 0,003 |
| 10000 | 0,004 | 0 |
| 100000 | 0,313 | 0,389 |

*Table 8e: Output Impedance Correlation – Positive Op Amp Based Regulators.*

| Frequency | R^2 to Score | R^ to Rank |
|---|---|---|
| 10 | 0,021 | 0,125 |
| 100 | 0,003 | 0,005 |
| 1000 | 0,019 | 0,003 |
| 10000 | 0,02 | 0,008 |
| 100000 | 0,241 | 0,311 |

*Table 8f: Output Impedance Correlation – Negative Op Amp Based Regulators.*

The Jung/Didden, Sjöstrom and NewClass D ("NCD") all appear to be closely "related". The NCD, however, being an OEM product does not have a published schematic, and in respect of their intellectual property, none is shown herein. The error amplifier/pass device current source for the NCD, an NE5534 does not appear to be bootstrapped in the same manner as the Jung/Didden and Sjöstrom. The pass device for the NCD is an insulated BD139, a blessing for the audiophile tweaker. The performance measurements obtained from the NCD are consistent with what was seen from the Jung/Didden regulator when a comparison of alternate opamps was conducted, suggesting that a faster device than the NE5534 might be beneficial to already quite good performance. The error amplifier for these three regulators should be characterized as low noise, high bandwidth and high current sinking ability.

The Burson regulator, another OEM product was quite pleasing in its performance. Again, we refrain from publishing a schematic for the Burson in respect of their intellectual property, but will comment that it uses a single 2SC2240 transistor for an error amplifier, a 2SK170BLF JFET current source for the pass device and local filtering and decoupling capacitors. The pass transistor, a 2SC5171 has an Ft of 200MHz whereas many other regulators settle upon the D44H11 with an Ft of 50MHz. The LED on the Burson regulator PCB indicates whether the device is "ON" or "OFF", but serves no apparent electrical/electronic function!

The surprise in the listening test was that the OEM regulators from Linear Technology performed in the top cohort. For a product which requires little in the way of effort to deploy, the paired LT1963A/LT3015 are recommended.

Quite frankly, we were somewhat disappointed that the Salas "Simple Shunt Regulator" did not garner listening panel ratings proportionate to the praise it has received in the DIY universe. The regulators were constructed on the printed circuit boards specifically designed for them and careful attention was paid to the selection of parts, closely following the instructions supplied by the vendor. The shunt device in each case was a MOSFET and not a bipolar transistor which may account for the disappointing listening experience. The "Salas Simple Shunt" seems to be a continuous work in progress, with improvements proposed on a routine basis by the author. Once a "reference design" is published we will be happy to re-examine it with our listening panel.

**What makes a "disappointing" regulator**

We were puzzled that some of the devices were ranked as "poor" by the panel. It turns out that you can have too much of a good thing:

- Attempts to bring the reference noise to nano-Volt levels with additional capacitance can reduce the bandwidth of the error amplifier and increase its effective impedance.
- If not in theory, then in practice actively filtering the unregulated voltage (Bybee and SuperTeddy) seemed to play havoc with the bass region.
- The Belleson Super Regulator showed some evidence of oscillation at 8.5MHz under certain conditions. Conversation with the designer indicated that a small ceramic bypass would eliminate this problem.
- Bypassing the adjust pin of the LM317/LM337 regulators significantly lowers the device noise[7]. Others have suggested, however, that going overboard with adjust pin bypass capacitor value impairs performance.

**Postlude: Some thoughts on the Jung/Didden Regulator**

Many DIY'ers have tried to improve upon the performance of the Jung/Didden regulator. Quite frankly, this device performs so well that many of the tweaks aren't just gilding the lily, they impair performance. The AD797 amplifier, owing to its very high bandwidth, can be problematic as it is easily excited into oscillation if strict care is not paid to wiring and shielding. In one case, the AD797 based Jung/Didden regulator was observed oscillating at 2.2MHz when it was removed from its chassis. In another case, the oscillation caused the SSM2019 low noise amplifier to (apparently) rail. On occasion I was able to see several local a.m. radio stations (with energy well above the ambient level at their frequencies) on my HP3577A Spectrum Analyzer when the AD797 regulator was not properly housed. For these listening tests an AD825AR operational amplifier was used without any bypass capacitors or RFI protection.

A few weeks after the listening tests were completed I took the time to examine the performance of different operational amplifiers in the Jung/Didden design. In addition to the AD797AN and AD825AR, I used the Linear Technologies LT1115 and Texas Instruments LME49710, NE5534 and OPA134. I found that the noise and output impedance could be improved from the levels attained with the AD825AR with the TI LME49710. Furthermore, the LME49710 remained stable under the various load condition which faced it. In general, the line rejection of the Jung/Didden regulator was not significantly affected by substituting different operational amplifiers as illustrated in **figure 11**.

In terms of noise, the AD797 still wins when compared to this cohort of operational amplifiers, see **figure 12**.

Output impedance for the AD797 again bests the competition, but the LME49710 is a strong con-

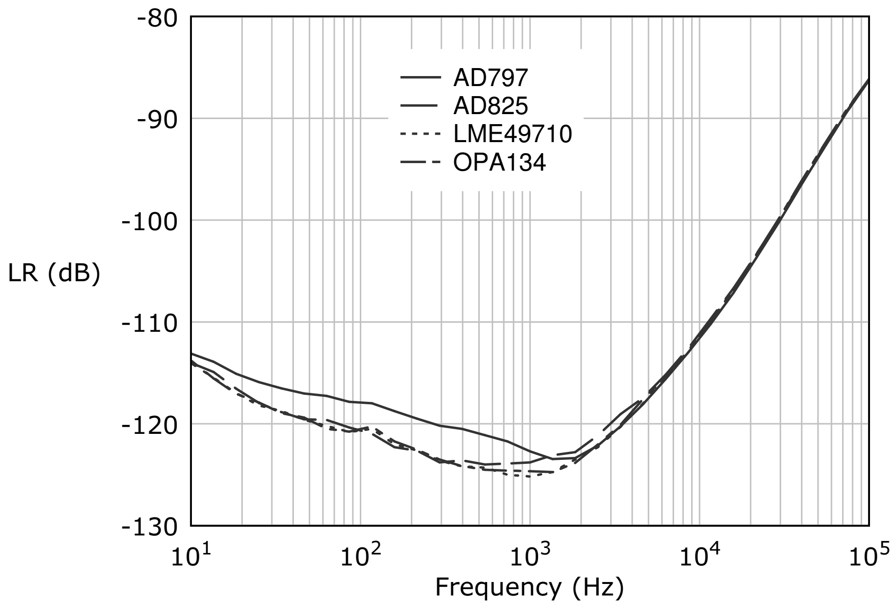


*Figure 11: Line Rejection of the Jung/Didden regulator with various opamps.*

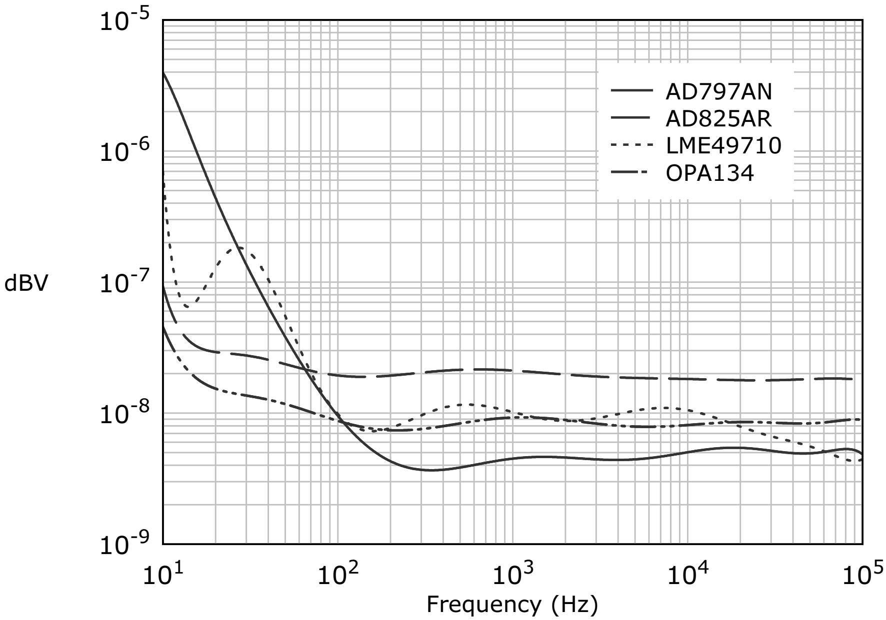


*Figure 12: Output Noise of the Jung/Didden regulator with various opamps.*

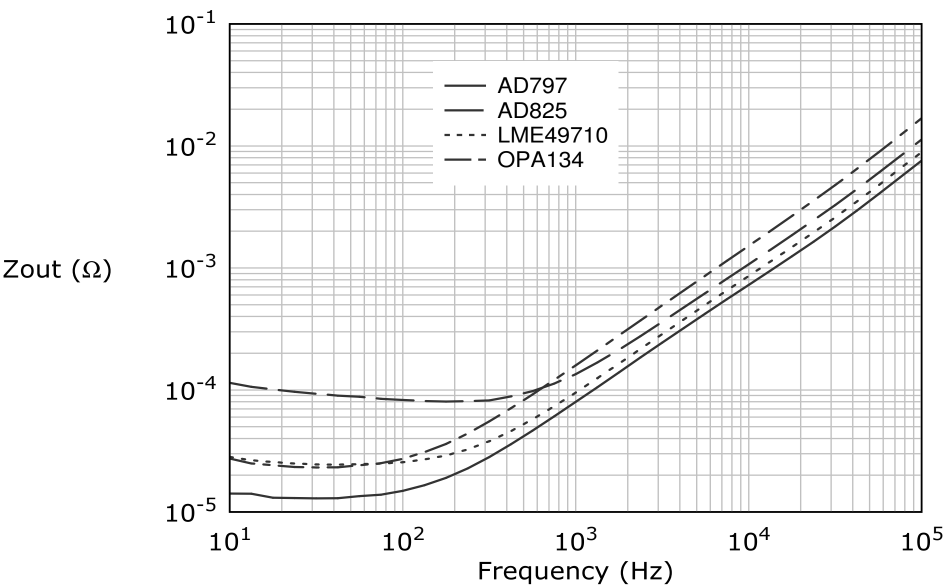


*Figure 13: Output Impedance of the Jung/Didden regulator with various opamps.*

tender. The impedance graph in **figure 13** illustrates a low "Z" of 13µΩ at 23Hz in the device with LM317 pre-regulator. In one of the AD797 based regulators without pre-regulation we were able to measure a low impedance of less than a microOhm.

The Jung/Didden regulators used for the listening test were built on the printed circuits once available from Old Colony Sound. Since these are no longer available, and given the closely related listening performance of the Sjöstrom Regulator to the Jung/Didden we suggest that those interested in a high quality, compact design contact Per-Anders Sjöstrom at www.sjostromaudio.com.

## References

1 Jung, Walt "Regulators for High Performance Audio", Audio Amateur 1/1995 pp 6-18
2 Kite, Tom "Tutorial: Measuring Complex Impedance with SYS-2722", Audio.TST, Audio Precision, www.ap.com, March 2008.
3 Borbely, Erno "The All-FET Line Amp", audioXpress 5/02 pp 28-33
4 K-Works, Clifton NJ.
5 Oue, Eiji "Rachmaninoff Symphonic Dances", Minnesota Orchestra, Reference Recordings 2001.
6 Jung, Walt "Improved Positive/Negative Regulators",Audio Electronics 4/00 pp 8-19
7 Dietz, Erroll "Understanding and Reducing Noise Voltage on Three-Terminal Regulators" in Pease, Robert A. "Troubleshooting Analog Circuits" Elsevier Publications, Oxford 1991 (Paperback edition 1993), pp 191-195.

## Bibliography and Suggested Reading

________, "Agilent Impedance Measurement Handbook", 4th Edition, Agilent Corporation, July 2009, www.agilent.com

________, "8 Hints for Succesful Impedance Measurements", Agilent Corporation, Application Note 346-4, www.agilent.com

________, "EIS Measurement of a Very Low Impedance Lithium Ion Battery", Gamry Instrument Corporation Application Note, www.gamry.com

________, "Measurement of Output Impedance of a Constant Voltage Power Supply", Hewlett Packard (Agilent Corporation), Technical Letter #40, www.hparchive.com

Basso, Christophe P. "Switch-Mode Power Supplies, SPICE Simulations and Practical Designs", McGraw Hill, NY 2008.

Dietz, Erroll H., "Understanding and Reducing Noise Voltage on 3-Terminal Voltage Regulators" in: Pease, Robert A. "Troubleshooting Analog Circuits", Newnes Elsevier, Oxford UK 1993.

Dostal, Frederick "Measure Power Supply Loop Transfer", EDN December 5, 2008 pp 47-49

Jung, Walter G. "Don't shun the shunt regulator", Electronic Design 14, July 5, 1969 pp 70-72.

Panov, Yuri and Jovanovic, Milan "Practical Issues of Input/Output Impedance Measurements in Switching Power Supplies and Application of Measured Data to Stability Analysis", available at http://www.deltartp.com/dpel/dpelconferencepapers/33.3_10275.pdf

Simon, Ed "Shunt Regulator, The Almost Forgotten Circuit", AudioXpress 6/07 pp 29-33

Simpson, Chester "Linear Regulators: Theory of Operation and Compensation", National Semiconductor Corporation Application Note 1148, May 2000.

Sulzer, Michael P. "A High Quality Power Supply Regulator for Operational Amplifier Preamplifiers", The Audio Amateur 2/1980 pp 8-12,47

Sulzer, Michael P. "Regulators Revisited", The Audio Amateur 1/1981 pp 10,11

Williams, Jim "Performance Enhancement Techniques for Three-Terminal Regulators", Linear Technology Corporation Application Note 2, August 1984. (Particularly figure 11a)

Williams, Jim "Performance Verification of Low Noise, Low Dropout Regulators", Linear Technology Corporation Application Note 83, March 2000.

## Appendix A – Instrumentation overview

The following test instruments were used in collecting data for this article.
Measurement Instruments: Audio Precision SYS-2722, Tektronix AA5001, Tektronix DM510
Oscilloscopes: Tektronix 3012B, Tektronix 2465A
Pulse Generator: Tektronix PG501
Power Sources: Hewlett Packard 6271B Variable Regulated Power Supply, Tektronix PS5010, Kepco BOP 100-4M.
Spectrum Analyzer: Hewlett Packard 3577A
Signal Sources: Audio Precision SYS-2722 192K, Tektronix SG5010

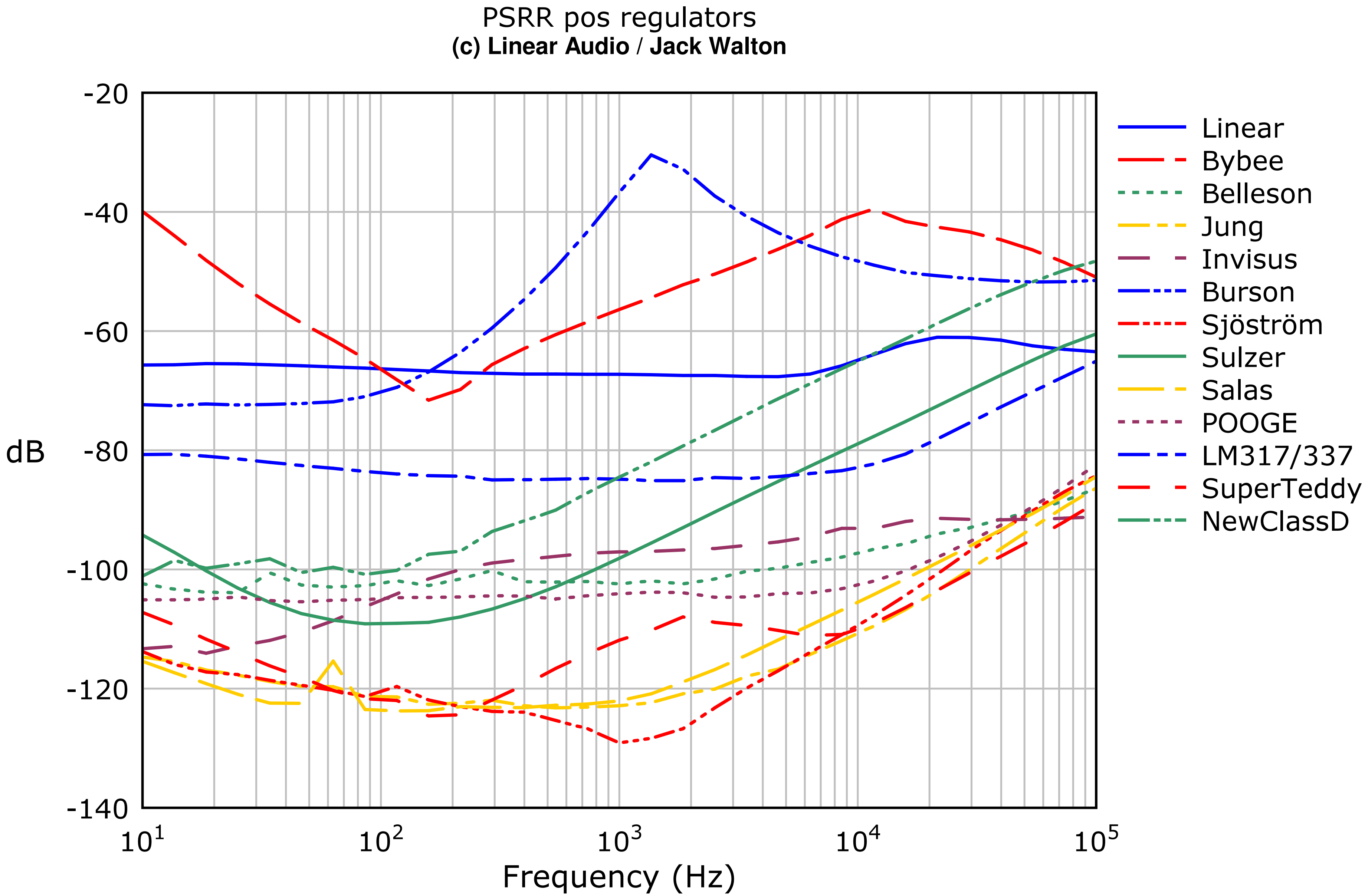


Figure 5: Line rejection measurements for the positive regulators.

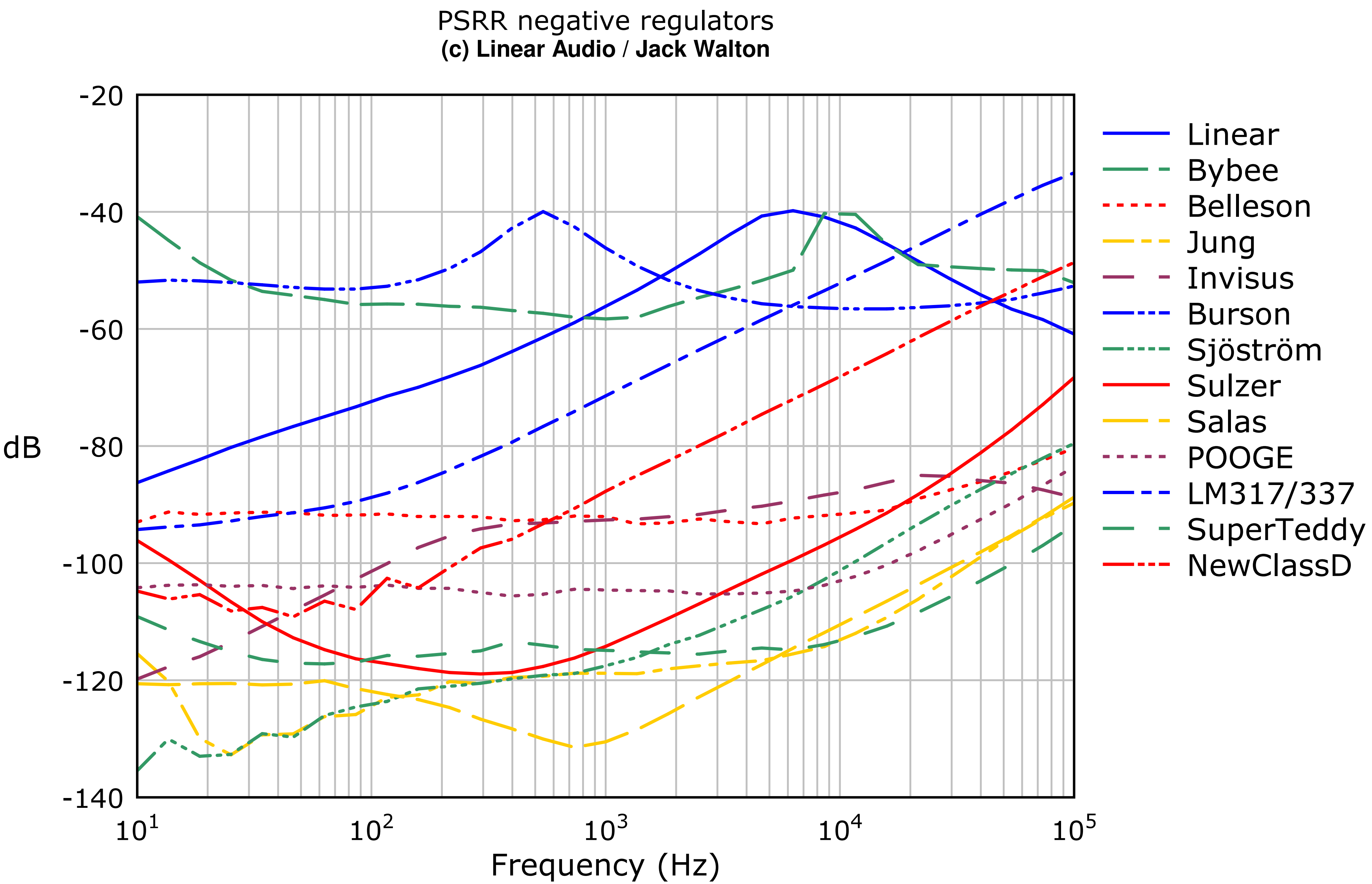


Figure 6: Line rejection measurements for the negative regulators.

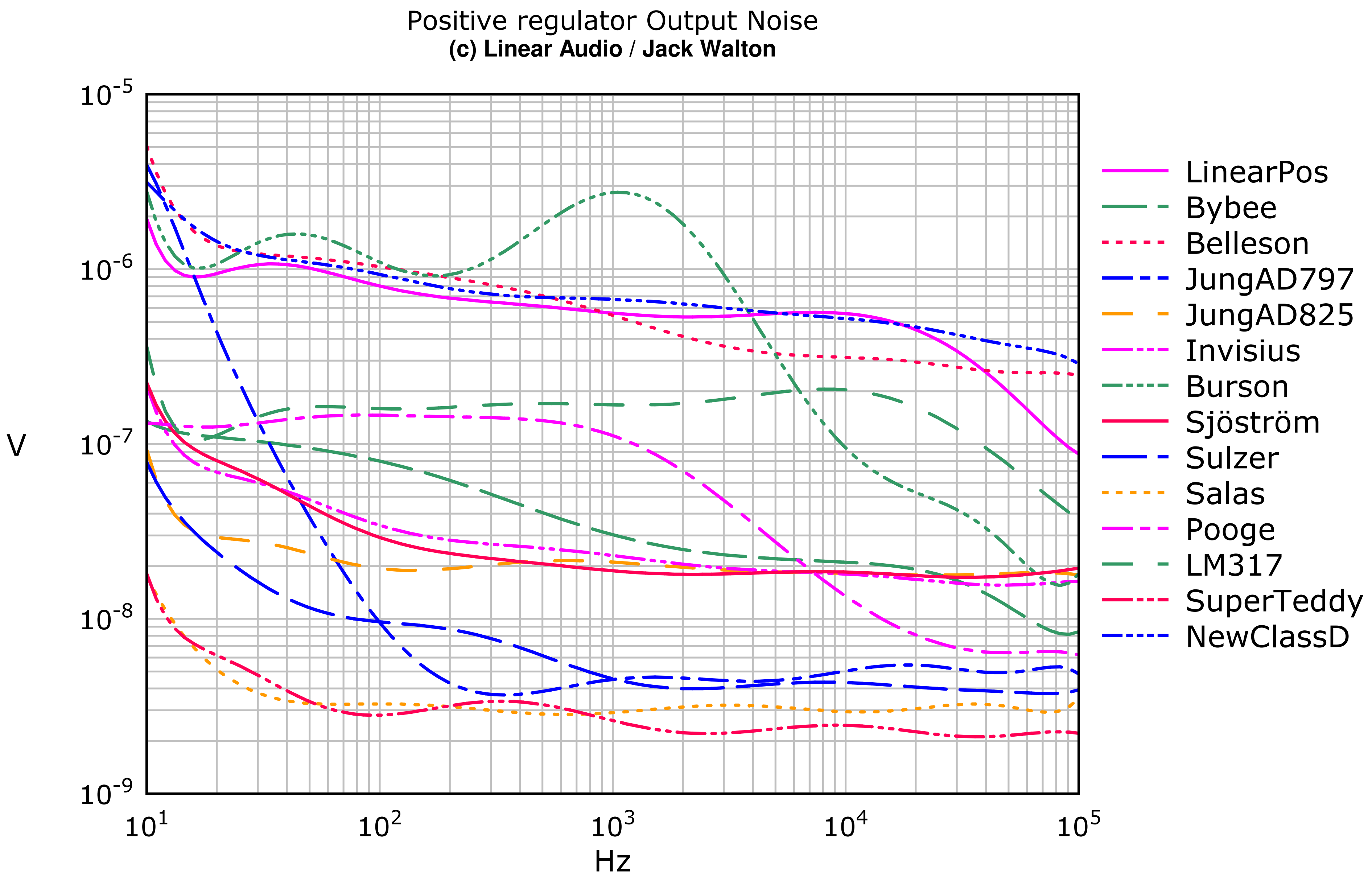


Figure 7: Positive Regulator Output Noise, computed as voltage per root Hertz.

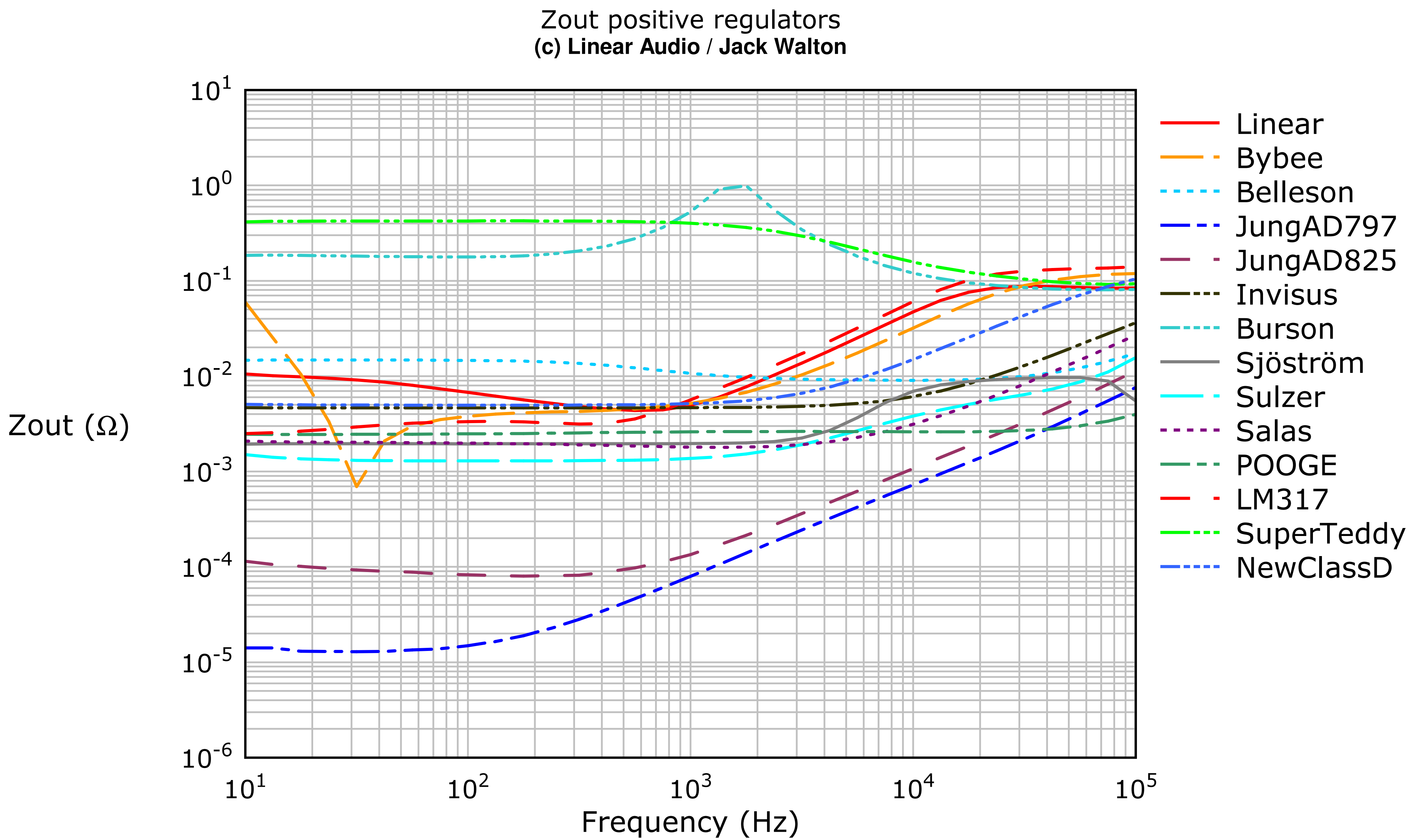


Figure 8: Positive regulator Output Impedance versus Frequency.

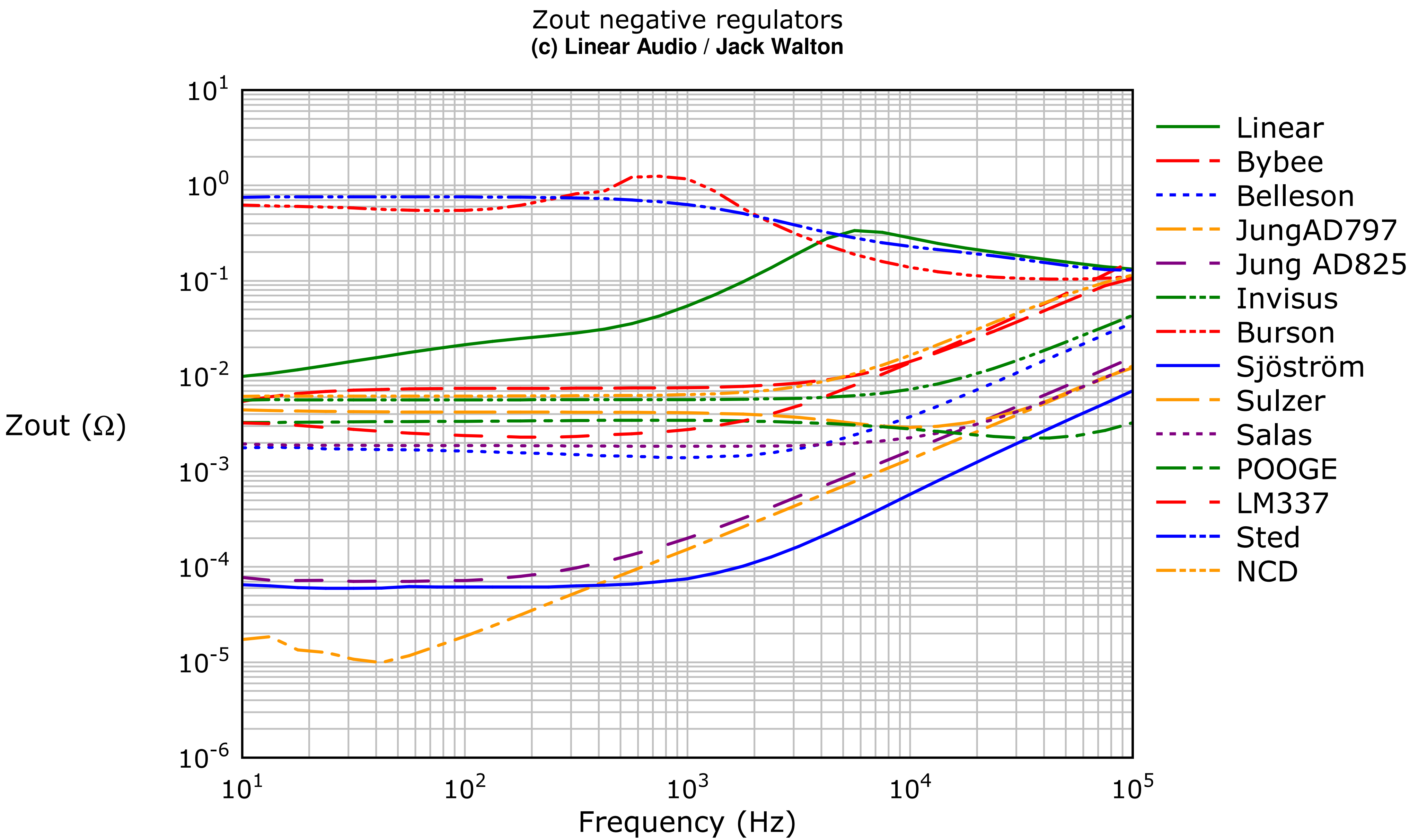


Figure 9: Negative regulator Output Impedance versus Frequency.

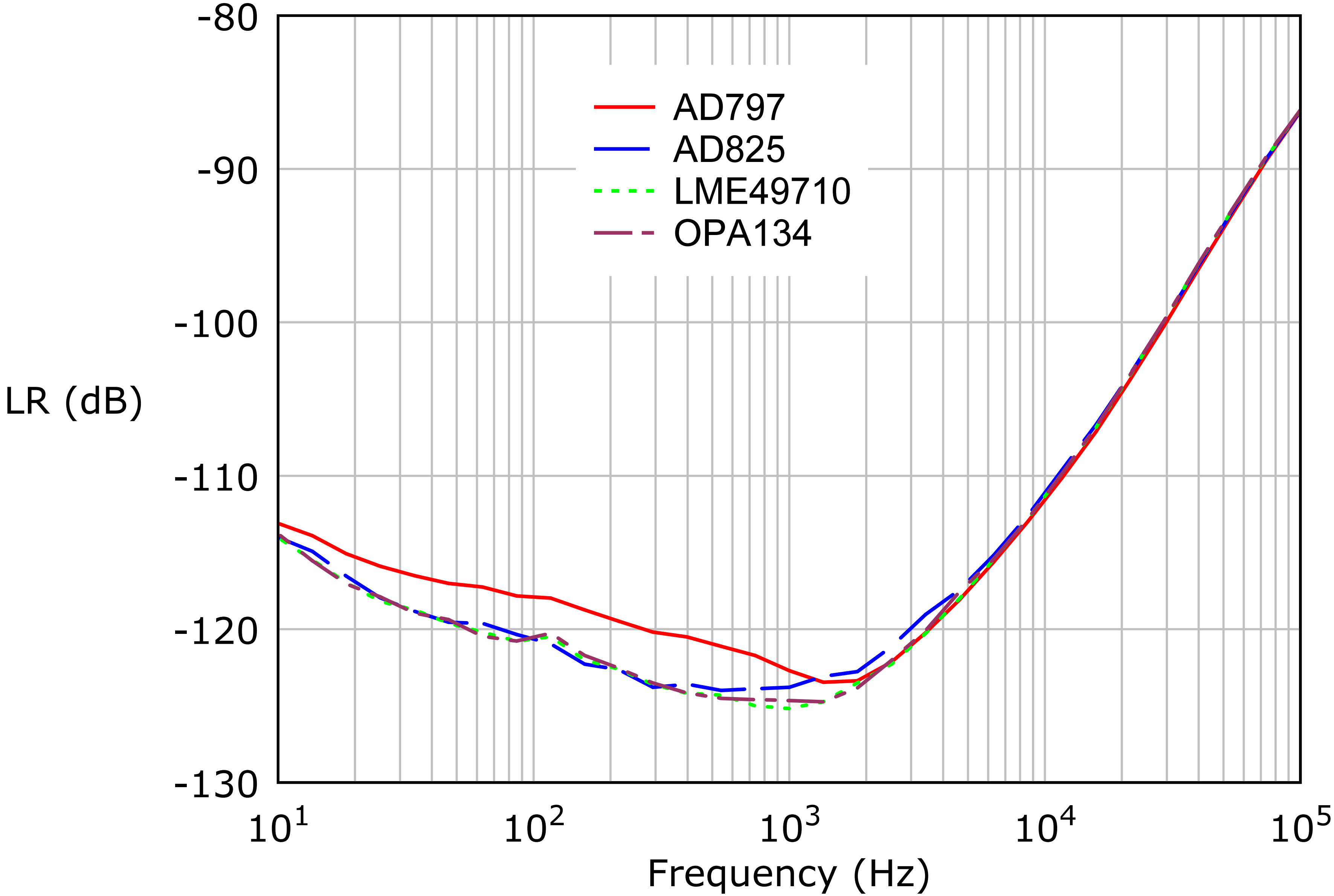


Figure 11: Line Rejection of the Jung/Didden regulator with various opamps.

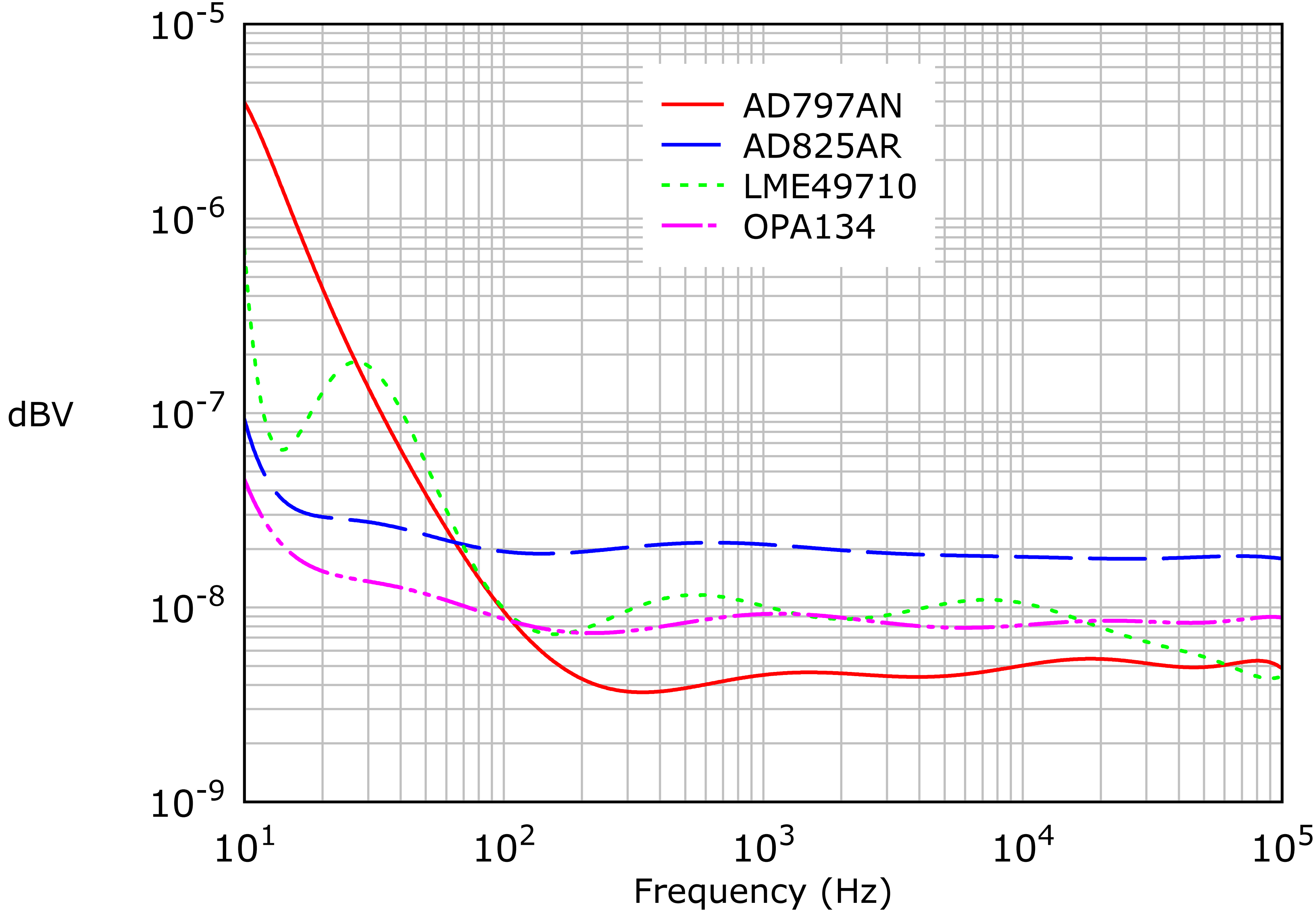


Figure 12: Output Noise of the Jung/Didden regulator with various opamps.

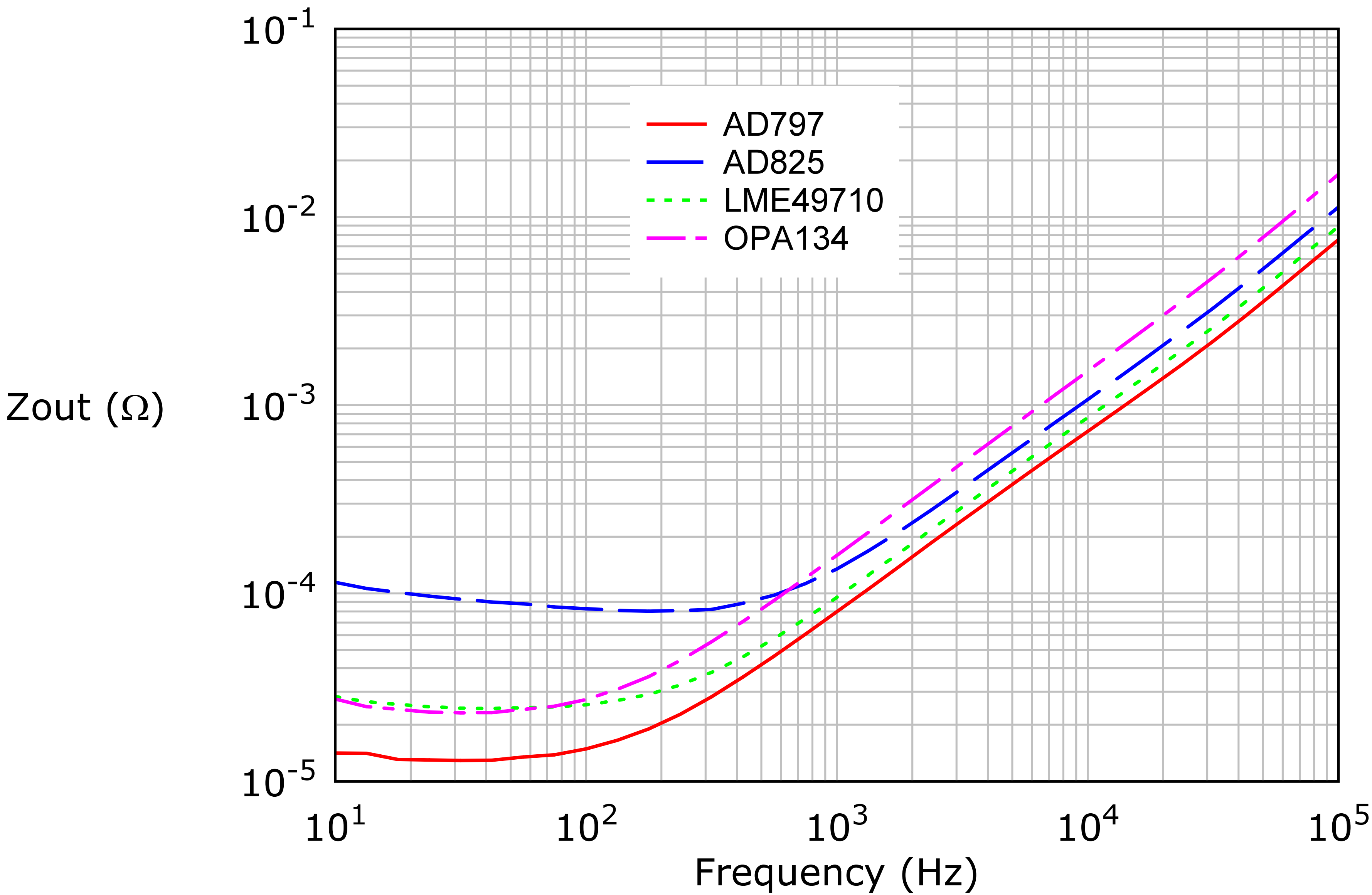


Figure 13: Output Impedance of the Jung/Didden regulator with various opamps.