

A Large Comparative Analysis of Loudspeaker Driver Distortion with Current Feedback Amplification*

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Loudspeaker drivers are almost always driven with amplifiers that use voltage feedback to improve linearity. However, for electrodynamic drivers, as per Lorentz law the electromotive force (EMF) that generates sound is proportional to the current passing through the voice coil – not the voltage across it. This suggests that improving current linearity may be a more effective strategy than improving voltage linearity. Although this has been demonstrated in prior works, existing studies have been limited in statistical power. We performed controlled testing of a diverse sample set of 31 electrodynamic loudspeaker drivers and conducted statistical analysis of their nonlinear behavior. Our results show that current feedback amplifiers significantly and reliably reduce 3rd and 5th order harmonic distortions produced by the loudspeaker drivers compared to voltage feedback designs. In addition, we show that this improvement translates into commercially significant added value.

0 INTRODUCTION

Linearity is one of the central design goals of any sound system. When it comes to audio amplifiers and loudspeaker drivers a lot of progress has been made with regard to linearity. Modern amplifiers achieve exceptional linearity. In parallel, measurement and modeling of loudspeaker drivers has advanced significantly and has become more accessible. Nevertheless, electrodynamic drivers (from now on we refer to them just as drivers) still exhibit significant nonlinearities, which manifest as current distortion [1, 2]. Notably, Klippel found that distortions from current-dependent inductance show up equally in the voice coil's current waveform and in the radiated sound output. These findings underscore that even with an ideal voltage amplifier, a driver's nonlinear electrical characteristics can distort the sound.

Most modern sound systems (e.g. Soundbars, portable speakers, TVs, studio monitors, PA ...) are active. In many cases, the amplifier and drivers are housed in one package where each driver has its own dedicated amplifier channel. This integration presents an opportunity to further improve the linearity of the amplifier-driver system without increasing cost by controlling the voice coil current.

With a large and diverse sample set, we demonstrate that on average current feedback amplification reduces 3rd and 5th-harmonic distortions in the midrange by 11dB and 5dB, respectively — equivalent to a performance improve-

ment typically associated with significantly more expensive drivers.

1 Method

1.1 Driver sample

A central aim of this study is to establish our results with more statistical power than in previous studies. To this end, we collected a sample of 31 commercially available drivers. The sample covers driver sizes of 9 to 20 cm cone diameter with the intended uses of woofer, midwoofer, midrange, or fullrange. Furthermore, various motor-magnet designs are present in our sample. A full list of manufacturers and model numbers can be found in Table 1 in the Appendix.

1.2 Hardware

The drivers are surface mounted in the center of a 40x40 cm panel with an NTI Audio M2010 microphone placed 25 mm from the surface of the panel.¹ The microphone feeds into a Quant Asylum QA472 preamplifier which then feeds a Quant Asylum QA403 audio analyzer.

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¹We deliberately placed the microphone in the near field to minimize the influence of driver size on acoustic output. This approach reduces the effect of size-dependent variations in acoustic efficiency, allowing for a fairer comparison of distortion across drivers of different diameters. Unlike fixed-SPL far-field testing, our method prioritizes consistent electrical drive conditions over absolute sound pressure levels.

A Texas Instruments TPA3255 amplifier (in bridge-tied load configuration) with post-filter feedback (PFFB) was used to power the drivers. The amplifier met Texas Instrument's published results in terms of noise and distortion [3]. However, one channel was modified to incorporate current feedback. The current feedback channel achieved an output impedance of 60Ω and transconductance of 1.75 A/V. Each driver was measured once with the voltage feedback (VF) channel and once with the current feedback (CF) channel.

1.3 Software

The aim of this work was to study the effect of current feedback on linearity. We chose to measure harmonic distortion as a measure of linearity, because of its ease of measurement and that it correlates reasonably well with other forms of nonlinearity. We use an exponential sweep [4] to measure impulse response and harmonic distortion at the same time. Our sweep goes from 60 to 24 kHz.

1.3.1 Flattening the Acoustic Output

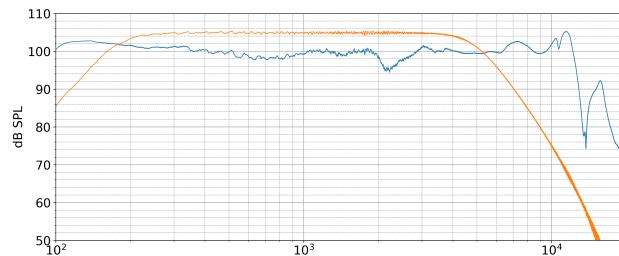


Fig. 1. An example of the two-measurement method. First a measurement (blue) is obtained by using a flat (uncompensated) exponential sweep. Then a second measurement (orange) is obtained using the 'compensated' exponential sweep that results in a flat acoustic output at 105 dB at the microphone. (Green is the noise floor)

Because drivers are reactive loads, their impedance and acoustic output vary significantly with frequency; especially when switching between voltage and current feedback amplifiers. This variation could confound harmonic distortion measurements if the input signal produces different frequency responses under each condition.

To isolate nonlinear behavior, we implemented a compensation technique based on inverse filtering. First, we measured the system's linear impulse response (including driver, amplifier, and baffle interaction) using a standard exponential sweep. We then computed the inverse of this impulse response and convolved it with a second sweep to generate a "compensated" stimulus. When this corrected sweep is played through the system, it results in a nearly flat acoustic output (± 0.5 dB) between 200 Hz and 4 kHz at 105dB SPL, as shown in Figure 1.

This method ensures that both the VF and CF measurements are made under identical acoustic output conditions, removing frequency-dependent response as a variable. It also makes cross-driver comparisons more meaningful by normalizing their on-axis output.

Figure 1 shows an example of the two-measurement method described above, first a measurement (blue) obtained by using a flat (uncompensated) exponential sweep. Then a second measurement (orange) is obtained using the 'compensated' exponential sweep that results in a flat acoustic output at 105 dB at the microphone. We use the flattened response (produced by the compensated sweep) to compute harmonic distortions.

2 Results

For each of the 2nd, 3rd, and 5th harmonics we take the average dB level over the 200 to 4 kHz range as a summary metric for their midrange linearity. This range was chosen because 1. All drivers in our sample are expected to cover most of this range. 2. Human hearing is most sensitive (to nonlinear distortions) in this range.

2.1 Relative performance change

The bar graph in Figure 2 shows the change in the average harmonic distortion for each driver for H2, H3, and H5 when we switch from VF to CF. We see the greatest improvement in H3 followed by H5. We also see a modest improvement in H2 for the more affordable drivers. It should also be noted that H5 was typically >10 dB closer to the noise floor of our measurement setup. So the fact that we see smaller improvements (compared to H3) is likely an artifact of our measurements.²

2.2 Competitive Ranking Analysis

We are interested to see how switching from VF to CF amplification can give a product a competitive advantage in terms of linearity. To do that we rank all drivers according to their average H3 and H5 performance with VF amplification. For each driver we then see how it would have ranked if it was driven with a CF amplifier. We see that on average a driver leapfrogs over 66% of its competition when ranked for H3, and 50% when ranked for H5. See Table 1 and Table 2 in the Appendix for a more granular view.

2.3 Cost-Performance Analysis

To highlight the commercial value of CF amplification, we would like to quantify the performance gain not only in dB values but also in its monetary value. Therefore we are interested to see how price correlates with harmonic distortions. Since drivers in our sample are of various sizes, their size/weight presents a major confounding factor in price. To normalize this factor away, we divide their unit price by their unit weight. We call this the "normalized price".

Figure 3 presents the three scatter plots for H2, H3, and H5 respectively. Each dot represents the distortion measurement for a driver. Blue indicates the measurement with

²Our sample of W8-1808 had a mechanical issue that produced loud high-order harmonics within a narrow frequency range. As a result, we suspect it was benefiting from the higher damping factor of VF and therefore shows a degradation in H5 with CF.

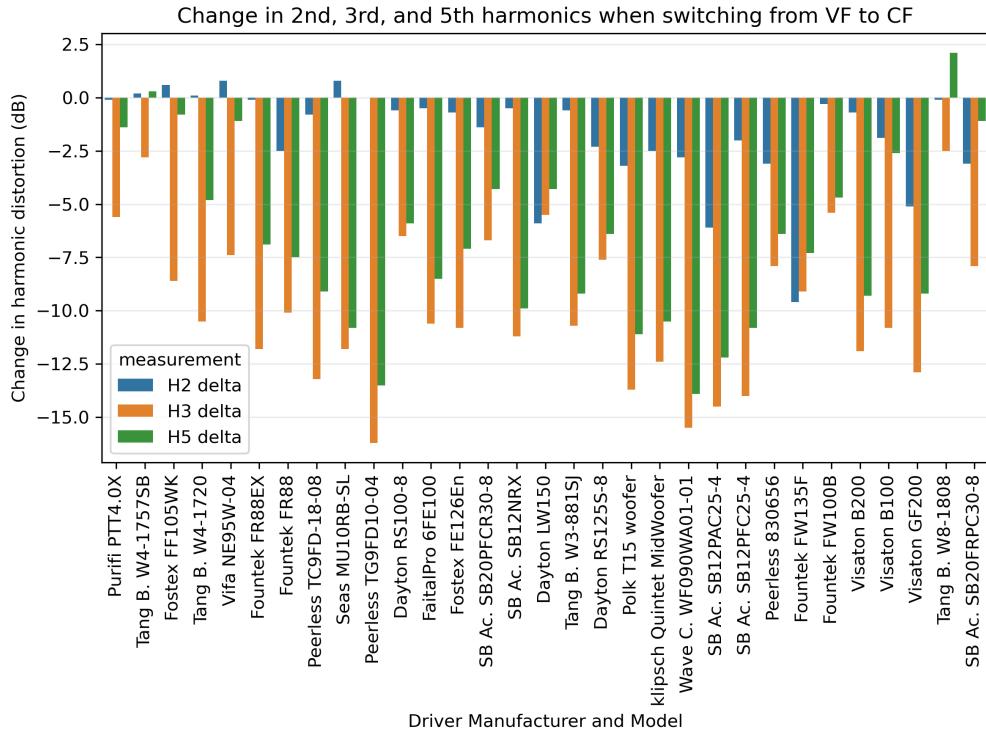


Fig. 2. The relative change in the harmonic distortion (HD) level when moving from VF to CF amplification. Negative numbers indicate a reduction in HD with CF amplification.

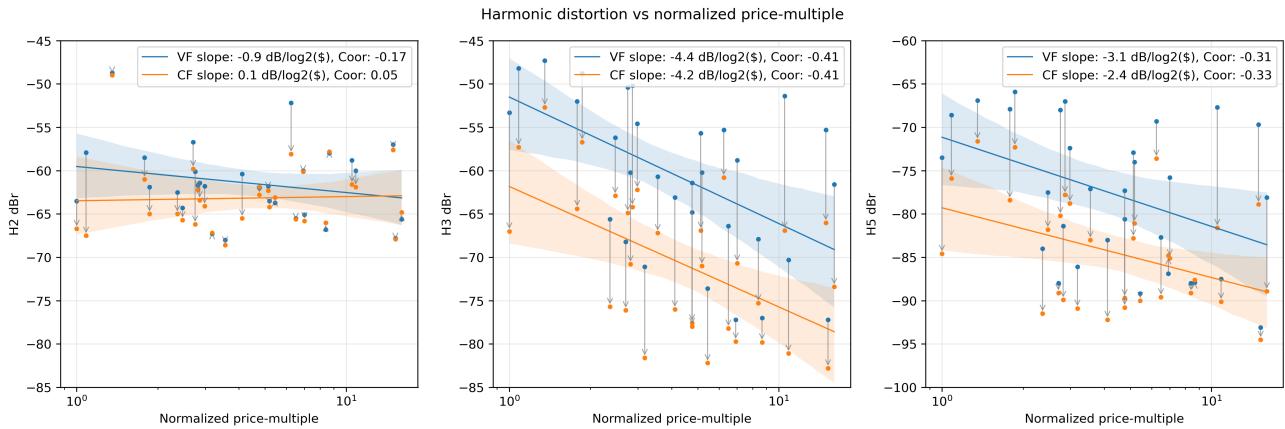


Fig. 3. Harmonic distortion (HD) vs. the normalized price-multiple. Each blue dot indicate a driver's HD level with VF and the orange dot pointed with an arrow indicated that same drivers HD level with CF. Blue and orange lines are best fit regression lines.

VF amplification and orange with CF. Y-axis are the dB values relative to the fundamental. X-axis is the normalized price divided by the price of the least expensive driver, so it represents price multiples. The blue and orange lines represent the best fit regression line to VF and CF measurement, respectively. Key observations:

- 1) We see a negative correlation between normalized price and harmonic distortions. In particular, we see Pearson r values of -0.4 and -0.3 for H3 and H5, respectively. This is true for both VF and CF amplification.
- 2) We see that the best-fit line for CF has shifted down by about 11dB for H3 and 7dB for H5. These val-

ues correspond to the expected improvement when switching from VF to CF amplification.

- 3) We can equivalently say that the H3 and H5 best fit lines for CF have shifted to the left. This shift is approximately a six-fold decrease in normalized price for H3/5. This suggests that for a typical driver, when powered by a CF amplifier, we can expect to see a H3/5 performance that rivals a driver 6 times its price. This level of improvement is not only of academic interest; it represents a price-to-performance shift large enough to influence real-world purchasing decisions.

3 Limitations

While this study compares a large number of drivers under controlled conditions, several limitations should be noted. First, we tested all drivers at a single signal level (i.e. 105 dB SPL at 25 mm) that was selected as a reasonable middle ground. However, nonlinearities are dependent on the level, and to get a more comprehensive view of a driver's performance, it should be tested at multiple levels.

Second, drivers have different intended bandwidths. For example, 20-cm drivers are not generally meant to reproduce up to 4 kHz and not all smaller 9-cm drivers are designed to reproduce 200 Hz. This resulted in some drivers being less favorably ranked.

Third, price normalization by weight was done to eliminate driver size as a confounding factor in their price, which allows us to compare drivers of different sizes. However, it is a rather crude method, and does not take into account other factors (like basket material) which may affect the weight, but not the nonlinear performance.

Finally, we focused on HD as the nonlinearity of interest, but there are other measures of nonlinearity such as two-tone intermodulation distortion, multitone distortion, and more recent techniques like FSAF [5] that can use arbitrary stimulus (e.g. music) as the test signal.

4 Conclusion

This study demonstrates that current feedback (CF) amplification can significantly improve the midrange linearity of electrodynamic loudspeaker drivers. By testing 31 commercially available drivers and carefully controlling for frequency response and test conditions, we found that CF amplification consistently reduces 3rd and 5th harmonic distortion by 11dB and 7dB (on average), respectively. These improvements are both statistically significant and practically meaningful, as they equate to performance gains typically associated with substantially higher-cost drivers.

From a product engineering standpoint, our analysis shows that integrating CF amplification into active loudspeaker systems can elevate the perceived quality of low-

and mid-tier drivers, potentially allowing them to compete with drivers priced several times higher.

While previous demonstrations of CF benefits have been limited in scope, our broader sample and comparative analysis provide a compelling case for CF as a viable, cost-effective strategy for enhancing driver performance in modern active speaker systems. Future work could explore perceptual testing and applicability to other driver types, such as tweeters and compression drivers.

5 REFERENCES

- [1] W. Klippel, "Measurement of Large-Signal Parameters of Electrodynamic Transducer," presented at the *107th Audio Engineering Society Convention* (1999 Sep.), aES Preprint 5008.
- [2] W. Klippel, R. Werner, "Measurement and Perception of Regular Loudspeaker Distortion," *Voice Coil (reprinted as Measurement and Perception of Regular Loudspeaker Distortion in AudioXpress)* (2011), URL <https://audiopress.com/index.php/article/Measurement-and-Perception-of-Regular-Loudspeaker-Distortion>, originally published in *Voice Coil*, May 2011; reprinted June 3, 2015 in *AudioXpress*.
- [3] D. Kisling, M. Beardsworth, "TPA324x and TPA325x Post-Filter Feedback," Application Report, SLA A788A SLAA788A, Texas Instruments, Dallas, TX, USA (2017 Sep.), URL <https://www.ti.com/lit/an/slaa788a/slaa788a.pdf>.
- [4] A. Farina, "Simultaneous Measurement of Impulse Response and Distortion with a Swept-Sine Technique," presented at the *108th Audio Engineering Society Convention* (2000 Feb.).
- [5] M. Zrull, "Fast Subband Adaptive Filtering (FSAF)," <https://www.mathworks.com/matlabcentral/fileexchange/83363-fast-subband-adaptive-filtering-fsaf> (2020), MATLAB Central File Exchange, retrieved November 25, 2020.

APPENDIX

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Table 1. Average H3 distortion ranking and values with voltage and current feedback for all drivers in the 200 Hz-4 kHz range.

Manufacturer Model	VF rank	CF rank	Percent beaten	H3 (dBr) CF	H3 (dBr) VF
Tang B. W8-1808	1	1	100	-79.7	-77.2
Purifi PTT4.0X	2	1	100	-82.8	-77.2
Tang B. W4-1757SB	3	1	100	-79.8	-77
Fostex FF105WK	4	1	100	-82.2	-73.6
Tang B. W4-1720	5	1	100	-81.6	-71.1
Visaton B100	6	1	100	-81.1	-70.3
SB Ac. SB20FRPC30-8	7	4	50	-76.1	-68.2
Vifa NE95W-04	8	4	57	-75.3	-67.9
Fountek FR88EX	9	1	100	-78.2	-66.4
Fountek FR88	10	4	66	-75.7	-65.6
Peerless TC9FD-18-08	11	1	100	-78	-64.8
Visaton GF200	12	4	72	-76	-63.1
Seas MU10RB-SL	13	5	66	-73.4	-61.6
Peerless TG9FD10-04	14	1	100	-77.6	-61.4
Dayton RS100-8	15	9	42	-67.2	-60.7
FaitalPro 6FE100	16	6	66	-70.8	-60.2
Fostex FE126En	17	6	68	-71	-60.2
Visaton B200	18	6	70	-70.7	-58.8
SB Ac. SB20PFCR30-8	19	13	33	-62.9	-56.2
SB Ac. SB12NRX	20	9	57	-66.9	-55.7
Dayton LW150	21	15	30	-60.8	-55.3
Tang B. W3-881SJ	22	10	57	-66	-55.3
Dayton RS125S-8	23	13	45	-62.2	-54.6
Polk T15 woofer	24	9	65	-67	-53.3
Klipsch Quintet MidWoofer	25	12	54	-64.4	-52
Wave C. WF090WA01-01	26	9	68	-66.9	-51.4
SB Ac. SB12PAC25-4	27	11	61	-64.9	-50.4
SB Ac. SB12PFC25-4	28	12	59	-64.2	-50.2
Peerless 830656	29	19	35	-56.7	-48.8
Fountek FW135F	30	19	37	-57.3	-48.2
Fountek FW100B	31	25	20	-52.7	-47.3

Siavash Rezaei holds a BSc in Systems Engineering from Simon Fraser University and an MSc in Applied Mathematics from Toronto Metropolitan University. From 2010 to 2015, he founded and led Serene Audio, specializing in speaker design and consumer audio systems. He

pursues independent research in loudspeaker distortion reduction techniques using feedback. He is currently preparing to launch Black Horse Audio as a design consultancy focused on transducer linearity.

Table 2. Average H5 distortion ranking and values with voltage and current feedback for all drivers in the 200 Hz-4 kHz range.

Manufacturer Model	VF rank	CF rank	Percent beaten	H5 (dBr) CF	H5 (dBr) VF
Purifi PTT4.0X	1	1	100	-94.5	-93.1
Fostex FF105WK	2	2	0	-90	-89.2
Vifa NE95W-04	3	3	0	-89.1	-88
SB Ac. SB20FRPC30-8	4	3	33	-89.1	-88
Tang B. W4-1757SB	5	5	0	-87.6	-87.9
Visaton B100	6	2	80	-90.1	-87.5
Tang B. W8-1808	7	7	0	-84.8	-86.9
Tang B. W4-1720	8	2	85	-90.9	-86.1
Fountek FR88	9	2	87	-91.5	-84
Visaton GF200	10	2	88	-92.2	-83
Fountek FR88EX	11	2	90	-89.6	-82.7
FaitalPro 6FE100	12	2	90	-89.9	-81.4
Peerless TC9FD-18-08	13	2	91	-89.7	-80.6
Seas MU10RB-SL	14	3	84	-88.9	-78.1
SB Ac. SB20PFCR30-8	15	12	21	-81.8	-77.5
Peerless TG9FD10-04	16	2	93	-90.8	-77.3
Dayton RS100-8	17	11	37	-83	-77.1
Visaton B200	18	9	52	-85.1	-75.8
Fostex FE126En	19	13	33	-81.1	-74
Polk T15 woofer	20	9	57	-84.6	-73.5
SB Ac. SB12NRX	21	11	50	-82.8	-72.9
Dayton RS125S-8	22	14	38	-78.8	-72.4
Tang B. W3-881SJ	23	14	40	-78.9	-69.7
Dayton LW150	24	20	17	-73.6	-69.3
Fountek FW135F	25	18	29	-75.9	-68.6
SB Ac. SB12PAC25-4	26	14	48	-80.2	-68
Klipsch Quintet MidWoofer	27	14	50	-78.4	-67.9
Wave C. WF090WA01-01	28	12	59	-81.6	-67.7
SB Ac. SB12PFC25-4	29	15	50	-77.8	-67
Fountek FW100B	30	23	24	-71.6	-66.9
Peerless 830656	31	23	26	-72.3	-65.9