Application Report
SLAA702–July 2016

TPA3251 and TPA3255 Post-Filter Feedback (PFFB)

Matthew Beardsworth

ABSTRACT

The TPA32xx Class-D audio amplifier family delivers tremendously high audio performance with less than 0.01% THD+N to clipping. The extremely high level of audio performance makes this device an ideal candidate for today's high resolution and high fidelity audio applications where previously, only Class-AB amplifiers could deliver the performance.

Since the TPA32xx family is an analog input closed loop (internal feedback network) Class-D audio amplifier, it is an ideal candidate for adding an additional Post-Filter Feedback or PFFB loop to further enhance performance. This application report shows one optional implementation of PFFB used on the TPA3251 and TPA3255 EVMs.

Benefits of PFFB:

- Improve audio performance (THD, IMD, and noise)
- Reduce inductor cost
- Reduce PCB area by using smaller inductors

NOTE: Actual component values for the end-application are determined by speaker impedance, stability requirements, and desired level of feedback.

Contents

1 EVM PFFB Implementation 2
1.1 Recommended Initial Component Values 4
1.2 EVM PFFB Component Location Reference 5
2 Closed Loop Gain 6
3 Performance Results 7
4 Benefits of PFFB 8
4.1 Reduction of LC Filter Distortion 8
4.2 Reduction of Output Noise 8
4.3 Improved Intermodulation Distortion (IMD) 9
5 Gain Compensation 10
6 Stability Analysis 11
6.1 Measuring Overshoot 11
6.2 Calculating Phase Margin 12
6.3 Open Load Testing - Worst Case for Stability 12
6.4 TPA3251 PFFB EVM Stability 13
6.5 TPA3255 PFFB EVM Stability 14
7 Further Reading 15

List of Figures

1 EVM PFFB Implementation 3
2 TPA3251EVM Schematic Zobel Network and Feedback Resistors 5
3 TPA3251EVM Schematic Input Resistor and Op-Amp Feedback Pole 5
4 TPA3251EVM PFFB vs Non-PFFB, 4 Ω, 600 kHz, 36 V 7

5 TPA3255EVM PFFB vs Non-PFFB, 4 Ω, 450 kHz, 51 V 7
6 Inductor Distortion Reduction in PFFB, 4 Ω, 600 kHz, 36 V 8
7 TPA3251 1-W SMPTE Distortion Non-PPFB vs PFFB 9
8 10-W SMPTE Distortion non-PPFB vs PFFB 9
9 Op-Amp Gain Compensation for 20-dB System Gain With Standard PFFB 10
10 Measuring Overshoot 11
11 Phase Margin vs Percent Overshoot (Refer to TI Precision Labs Op Amps: Stability) 12
12 TPA3251 PFFB Overshoot Unloaded 13
13 TPA3251 PFFB Overshoot 8-Ω Load 13
14 TPA3251 PFFB Overshoot 4-Ω Load 14
15 TPA3255 PFFB Overshoot Unloaded 14
16 TPA3255 PFFB Overshoot 8-Ω Load 15
17 TPA3255 PFFB Overshoot 4-Ω Load 15

1 EVM PFFB Implementation

Post filter feedback is implemented by adding a secondary feedback loop external to the amplifier. This feedback loop takes a fraction of the output voltage signal of the amplifier after the external LC filter and sends an error signal back to the input of the amplifier.

Figure 1 shows the basic PFFB implementation used throughout this document for the TPA3251 and TPA3255 EVMs. These EVMs were designed with the option to support PFFB by populating the necessary components.

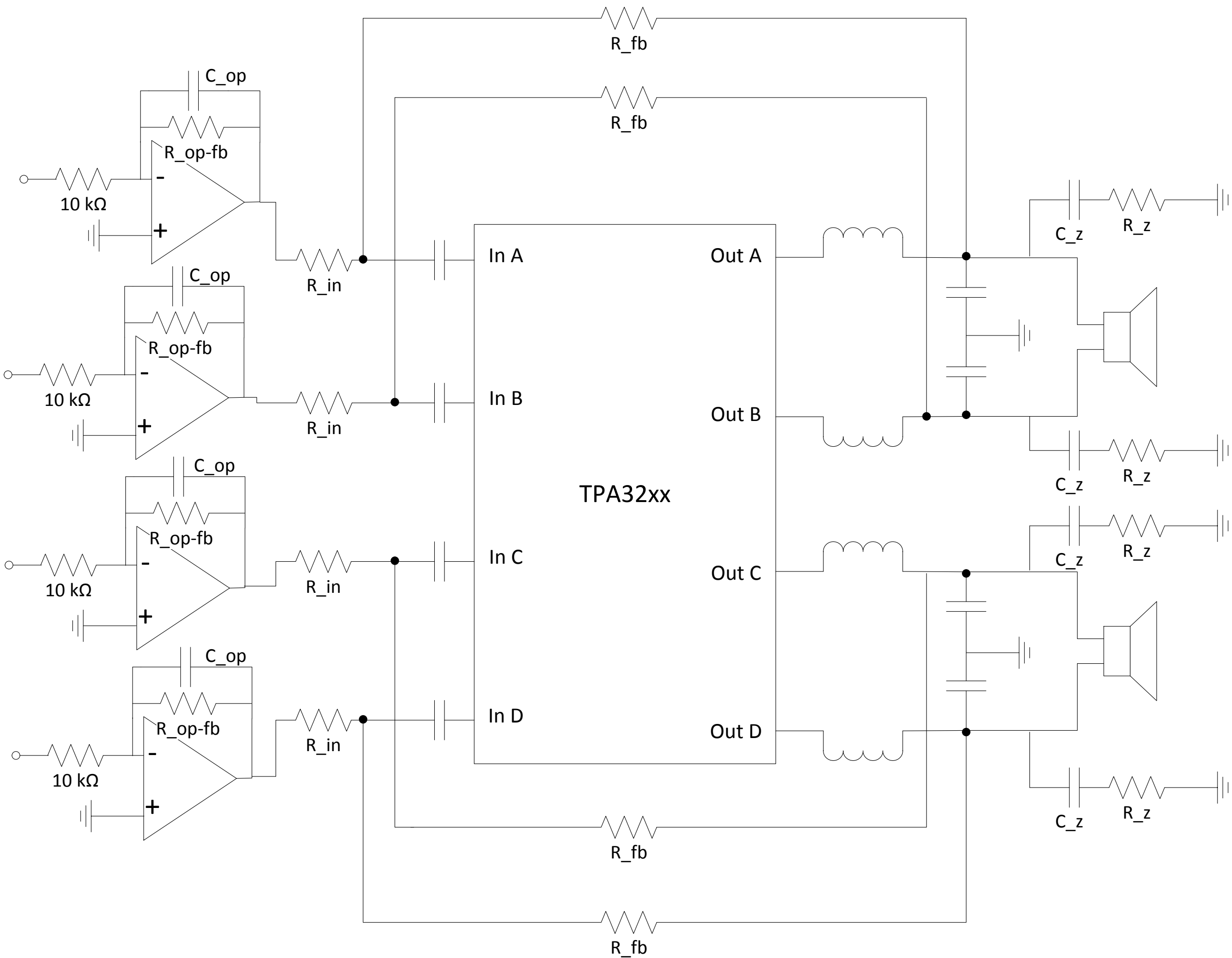


Figure 1. EVM PFFB Implementation

1.1 Recommended Initial Component Values

- R_fb: Feedback resistor
- R_in: Input summing junction resistor
- C_z: Zobel network capacitor
- R_z: Zobel network resistor
- C_op: Op-Amp feedback capacitor
- R_op-fb: Op-Amp feedback resistor

Table 1. Recommended EVM PFFB Component Values

PFFB Designator	EVM Schematic Location/Designator	TPA3251 (PVDD = 36 V, Fpwm = 600 kHz)	TPA3255 (PVDD = 51 V, Fpwm = 450 kHz)
R_fb	R47, R49, R50, R51	18 kΩ	20 kΩ
R_in	R4, R12, R44, R46	2.7 kΩ	2.7 kΩ
C_z	C77, C78, C79, C80	1 µF	1.33 µF (1 µf // 0.33 µf)
R_z	R54, R55, R56, R57	2.7 Ω	3.3 Ω
C_op	C18, C23, C57, C65	330 pF	330 pF
R_op-fb	R8, R41, R21, R25	10 kΩ	10 kΩ

R_z and C_z Zobel network is required for stability. The Zobel network helps attenuate high-frequency ringing by damping the amplitude response of the output LC filter and lowering Q factor. This is especially required for open-load stability where the Q of the LC filter is extremely large due to the lack of dampening from the load impedance. Reducing the Q of the output filter also increases stability, by relaxing the phase shift associated with a high Q system.

Since the higher voltage TPA3255 has larger PWM amplitude and slower nominal switching frequency compared to the TPA3251, the Zobel network needs to be adjusted to insure stability. Changing the switching frequency and PVDD supply voltage of either the TPA3251 or TPA3255 may require adjustment of the Zobel network.

C_op, the Op-Amp feedback pole, can be tuned as needed for desired HF response.

1.2 EVM PFFB Component Location Reference

Figure 2 and Figure 3 show the component location on the TPA3251EVM for PFFB implementation.

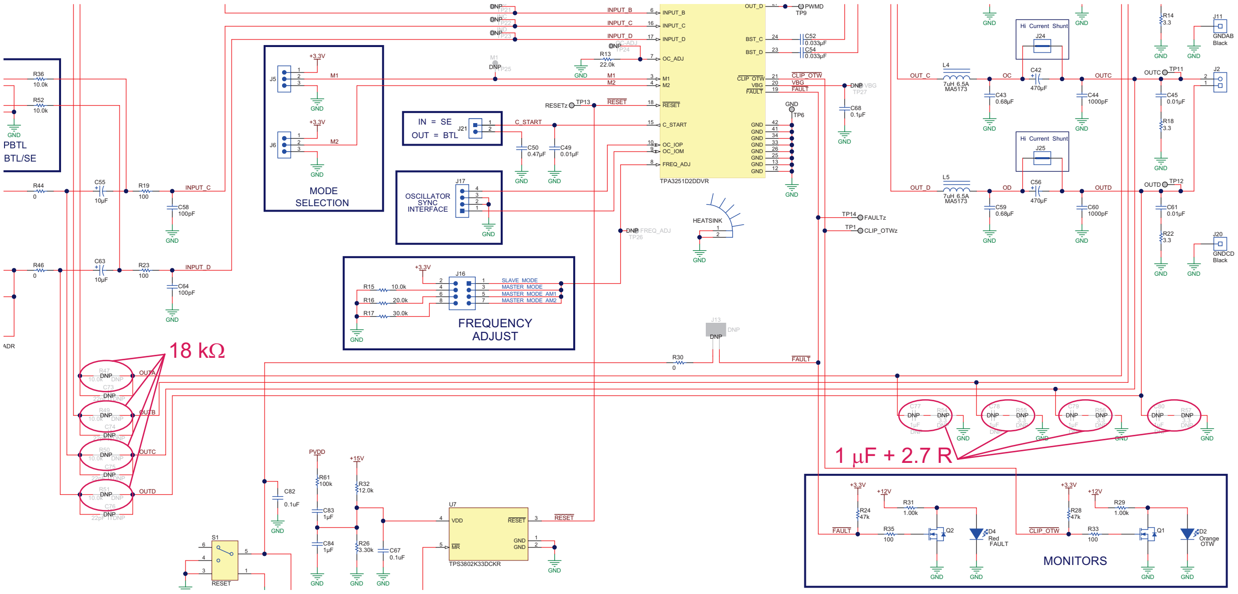


Figure 2. TPA3251EVM Schematic Zobel Network and Feedback Resistors

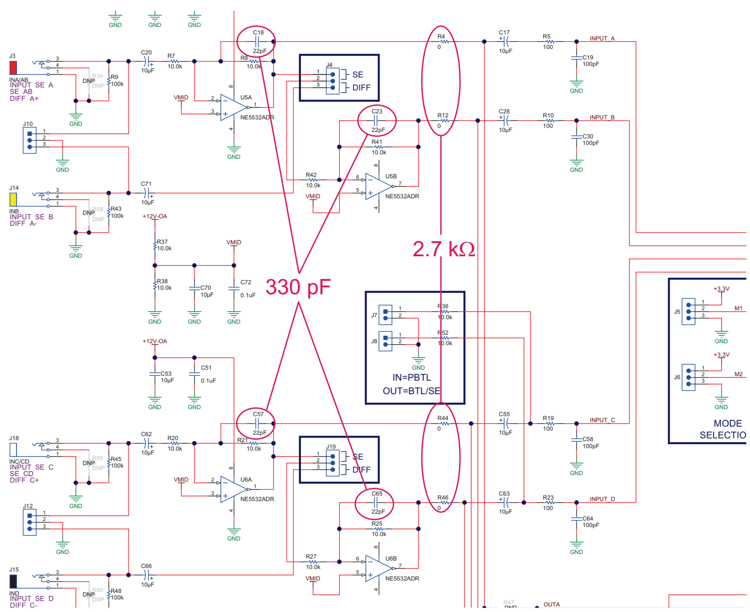


Figure 3. TPA3251EVM Schematic Input Resistor and Op-Amp Feedback Pole

2 Closed Loop Gain

With the components for PFFB selected and the gain on the amplifier known, the new closed loop gain can be estimated. Equation 1 shows the closed-loop gain.

$$A_f = \frac{A_0}{(1 + A_0\beta)} \tag{1}$$

Equation 2 is used to calculate constants for the TPA3251.

$$\beta = \frac{R\_in}{R\_in + R\_fb} \tag{2}$$

By plugging in the constants from Equation 2 into Equation 1, the closed loop gain for the TPA3251EVM PFFB implementation can be calculated:

$$A_0 = 20\text{ dB} = 10 \qquad \beta = \frac{2.7k}{(2.7k + 18k)} = 0.13$$

$$A_f = \frac{10}{(1 + (10 \times 0.13))} = 4.35 = 12.8\text{ dB} \tag{3}$$

- The closed loop gain has been reduced to 12.8 dB, due to PFFB.
- 7.2 dB of PFFB has been applied to the amplifier

Table 2. PFFB Parameters

Feedback Parameters	TPA3251 (PVDD = 36 V, Fpwm = 600 kHz)	TPA3255 (PVDD = 51 V, Fpwm = 450 kHz)
Gain Ao (dB)	20	21.5
Feedback Factor β	0.13	0.119
PFFB Gain Af (dB)	12.8	13.8
Negative Feedback (dB)	7.2	7.7

NOTE: With the TPA3251EVM, the actual gain in PFFB was measured to be 11 dB. With the TPA3255EVM, the measured gain was 12.2 dB.

The reduction in gain is primarily due to losses in the output inductor **and the non-zero output impedance of the input op-amp stage** not accounted for in the feedback factor β.

3 Performance Results

Figure 4 and Figure 5 show the TPA3251EVM PFFB vs Non-PFFB performance results at various conditions.

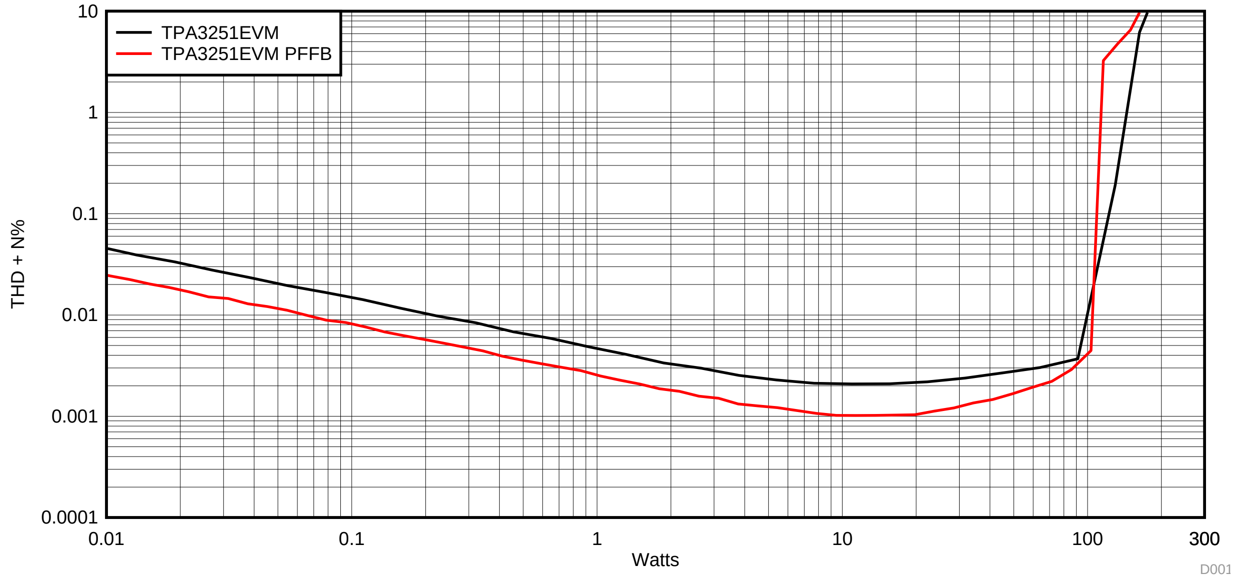


Figure 4. TPA3251EVM PFFB vs Non-PFFB, 4 Ω, 600 kHz, 36 V

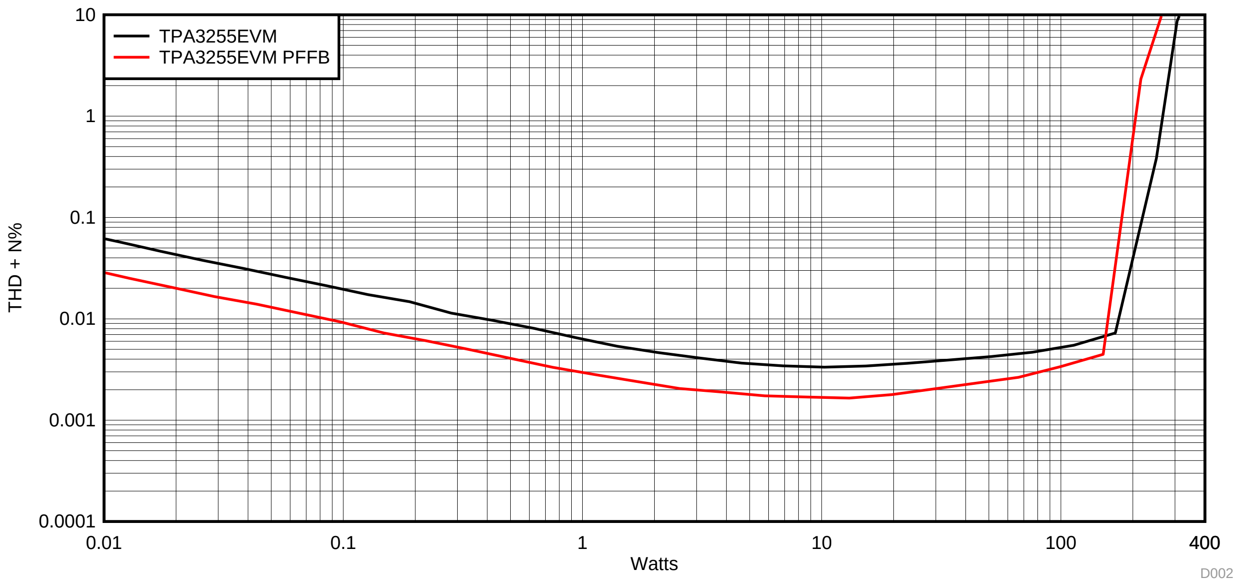


Figure 5. TPA3255EVM PFFB vs Non-PFFB, 4 Ω, 450 kHz, 51 V

4 Benefits of PFFB

For this section, measurements were taken using the standard PFFB implementation discussed in Section 1.

4.1 Reduction of LC Filter Distortion

The LC filter extracts a continuous analog audio signal from the PWM output for the Class-D to suppress radiating EMI and ripple current in the load connected. However, since the TPA32xx family offers such a high level of performance, the inductor used in the LC filter is the primary contributor to distortion. By feeding back the output after the inductor in PFFB, inductor distortion can be reduced significantly.

For systems where lower distortion is not a requirement, PFFB can allow for the use of a smaller and less expensive inductor while maintaining the standard level of performance offered by the TPA32xx amplifiers. Since smaller inductors are usually less linear and cause higher distortion, the distortion improvement offered by PFFB can allow very good system performance even with an inductor of this type.

Figure 6 illustrates the performance difference between 2 inductors, at 7 µH and 10 µH, before PFFB was applied. With PFFB, not only does the overall performance of the amplifier improve, but the performance gap between the two inductors has been reduced.

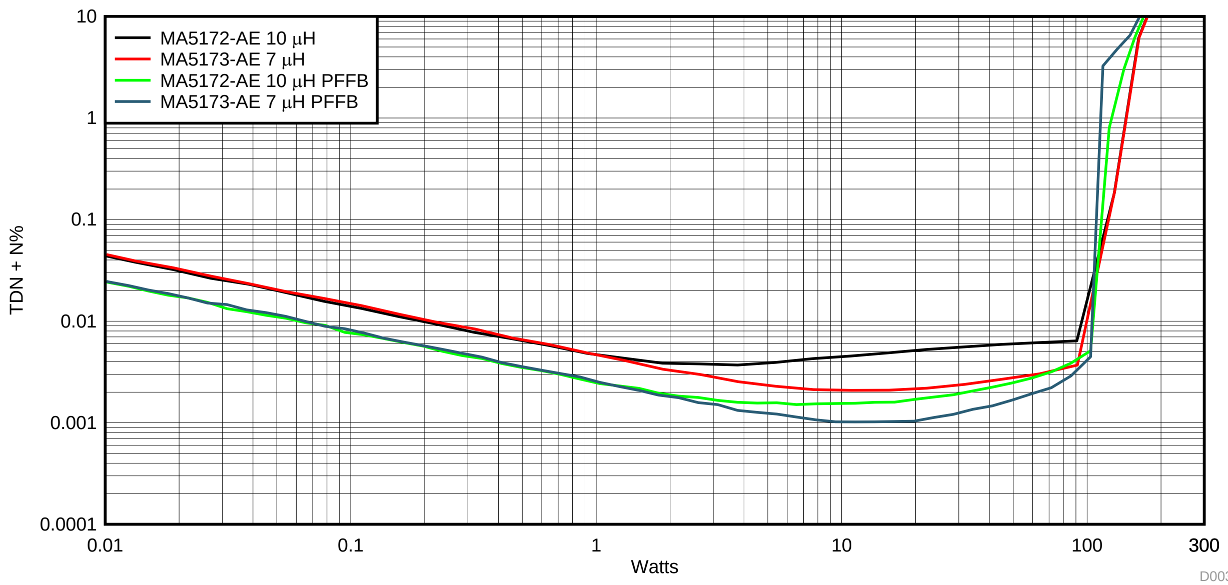


Figure 6. Inductor Distortion Reduction in PFFB, 4 Ω, 600 kHz, 36 V

4.2 Reduction of Output Noise

The output noise amplitude improves with PFFB.

Table 3. A-Weighted Output Noise

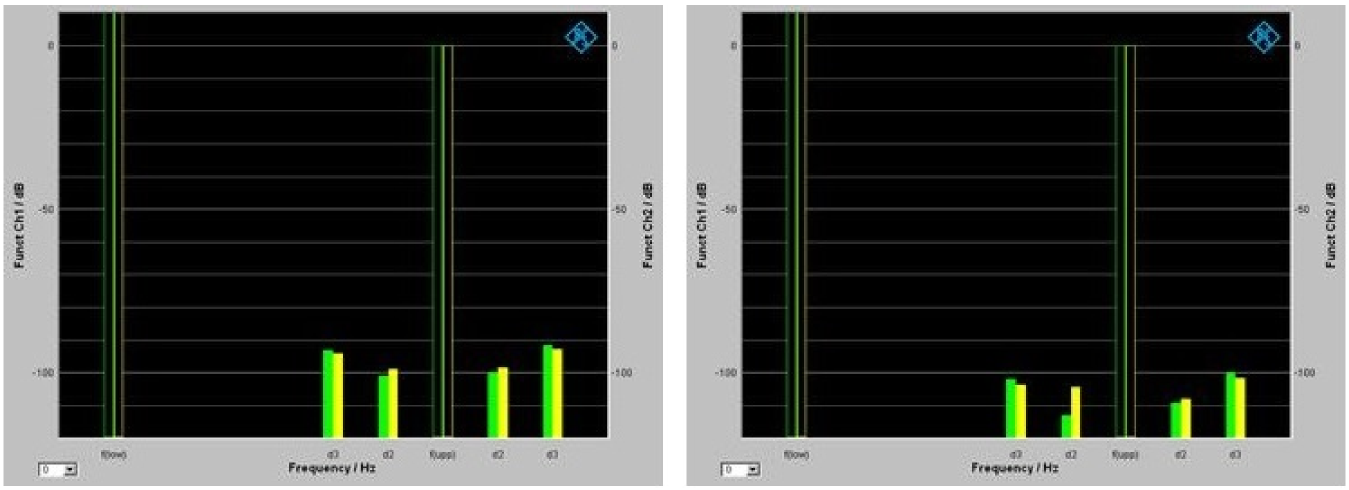
	Noise (µV) A-Weighted	
EVM Configuration	TPA3251 (PVDD = 36 V, Fpwm = 600 kHz)	TPA3255 (PVDD = 51 V, Fpwm = 450 kHz)
Standard	60 µV	86 µV
PFFB	35 µV	40 µV

4.3 Improved Intermodulation Distortion (IMD)

Intermodulation Distortion (IMD) looks at the harmonic content created by the mixing of two dissimilar sine wave tones in the amplifier. This test better represents a musical signal with lots of complex tones played simultaneously.

With this test, the IMD harmonic components have been reduced using PFFB, as shown by the FFT plots in Figure 7 and Figure 8.

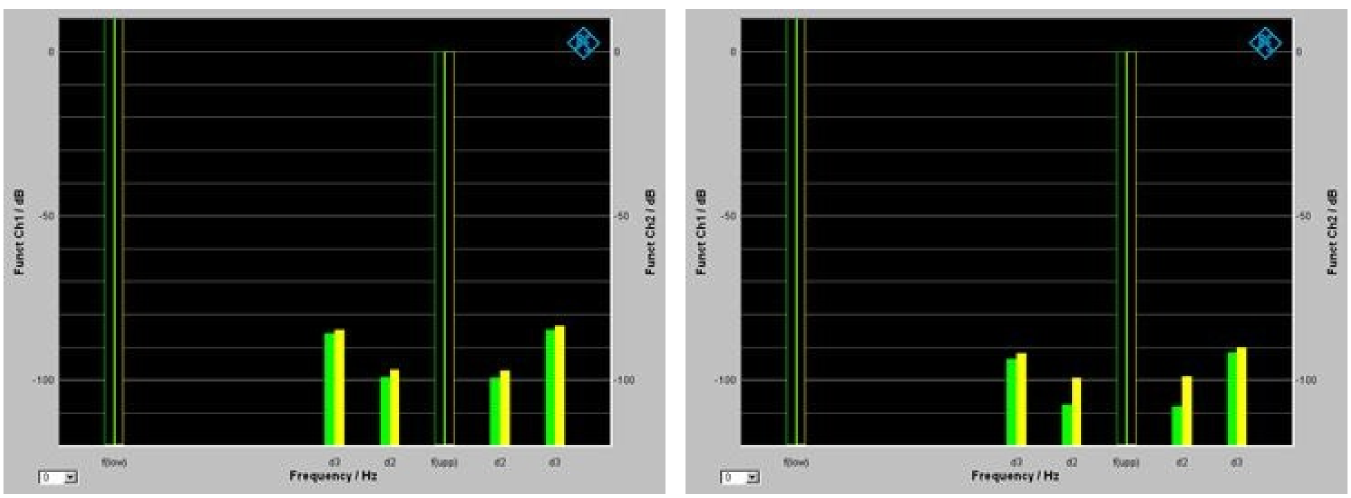
Test: SMPTE (60 Hz + 7 kHz, Ratio 4:1) 1 W, 8 Ω



TPA3251EVM TPA3251EVM with PFFB

Figure 7. TPA3251 1-W SMPTE Distortion Non-PPFB vs PFFB

Test: SMPTE (60 Hz + 7 kHz, Ratio 4:1) 10 W, 8 Ω



TPA3251EVM TPA3251EVM with PFFB

Figure 8. 10-W SMPTE Distortion non-PPFB vs PFFB

5 Gain Compensation

Since the measured closed loop gain of the TAP3251EVM and TPA3255EVM in PFFB is 11 dB and 12.2 dB respectively, the required input signal to reach maximum output power needs to be increased. By adding 9 dB and 9.3 dB back to the EVMs, the system gain is restored to 20 dB and 21.5 dB, respectively.

Table 4. Front End Op-Amp Gain Compensation

Gain	TPA3251 (PVDD = 36 V, Fpwm = 600 kHz)	TPA3255 (PVDD = 51 V, Fpwm = 450 kHz)
Measured Gain PFFB	11	12.2
Ideal Gain Compensation	9	9.3
Restored System Gain	20	21.5

This can be implemented by changing the feedback resistors R_op-fb of the input op-amps to 28 kΩ. This adds +9 dB of gain and is a good approximation for both the TPA3251 and TPA3255 EVMs.

- R_op-fb = R8, R41, R21, and R25 = 28 kΩ

Since the feedback resistor of the op-amp stage has been adjusted, for proper frequency response, capacitors C_op, C18, C23, C57, and C65 in the op-amp feedback path may also need to be adjusted. For testing with increased gain, these capacitors were changed to 100 pF.

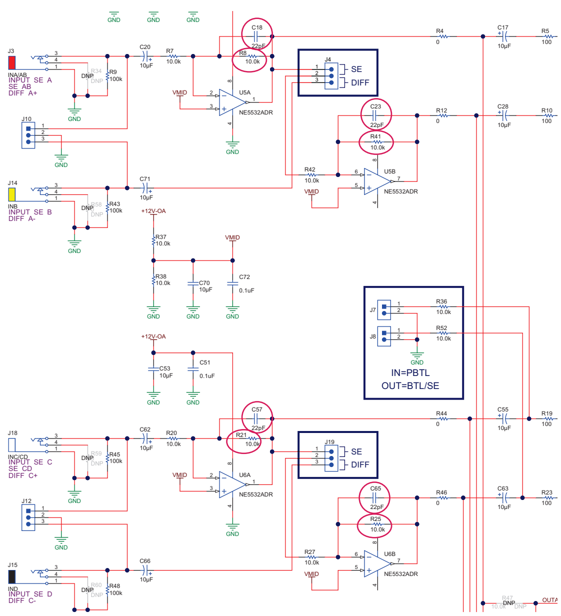


Figure 9. Op-Amp Gain Compensation for 20-dB System Gain With Standard PFFB

With added gain in the op-amp stages, the system gain with the TPA3251EVM in PFFB was measured to be 19.9 dB.

NOTE: With the following changes, only a true differential input on the EVM should be used since 9 dB of gain is applied to both input op-amp stages.

By increasing the gain of the EVM op-amp input stage, the op-amp output noise will also increase. This causes higher overall system noise even though the self-noise of the TPA32xx amplifier in PFFB has been significantly reduced.

To achieve lower overall system noise in PFFB with higher front end gain, considerations beyond the scope of the EVM must be taken to design a lower-noise op-amp front end with the desired system gain.

6 Stability Analysis

Stability analysis is important for PFFB to insure that the added outer PFFB loop does not cause amplifier oscillations. With incorrectly selected PFFB component values, poor stability margins can cause the amplifier to oscillate. This can cause the amplifier to shut down and behave erratically, especially near clipping.

6.1 Measuring Overshoot

Due to the native internal feedback loop in the TPA32xx amplifier family, frequency domain gain and phase analysis for stability assessment is difficult due to the inaccessible feedback loop internal to the device.. Further complexity is added since the PFFB loop includes the phase and amplitude characteristics of the output LC filter where the internal feedback loop does not.

For this reason, time domain overshoot analysis is the best means for assessing stability.

Using the TPA32xx EVMs setup in BTL PFFB outlined in Section 1, a 1-kHz square wave signal was injected into the input of the amplifier. The amplifier output was monitored on an oscilloscope to capture the amount of overshoot from the rising edge of the input square wave.

The amplifier output voltage of the square wave signal should be large enough for good resolution with the oscilloscope used for viewing the overshoot. However, the amplitude must not be large enough to approach clipping of the amplifier. The nonlinearity of clipping will give inaccurate results.

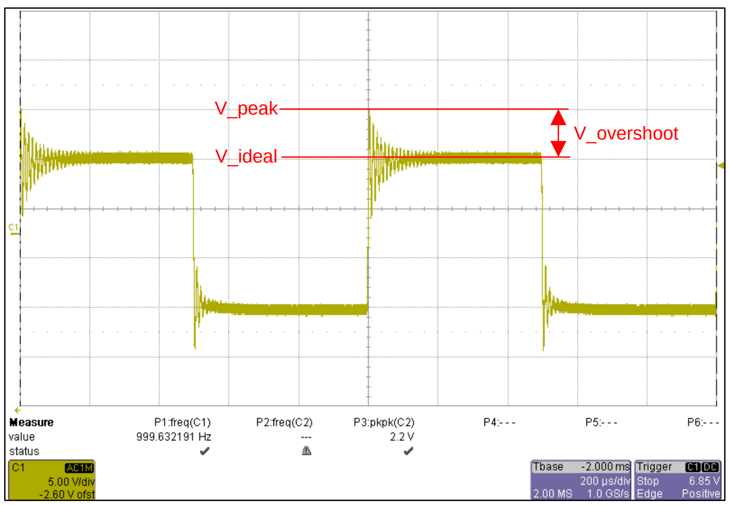


Figure 10. Measuring Overshoot

Use Equation 4 to calculate percent overshoot.

$$\text{Overshoot}(\%) = \left(\frac{(V\_peak) - V\_ideal}{V\_ideal} \right) \times 100 \quad (4)$$

6.2 Calculating Phase Margin

After the overshoot voltage level has been captured and the percent overshoot is calculated, the phase margin is found using Figure 11.

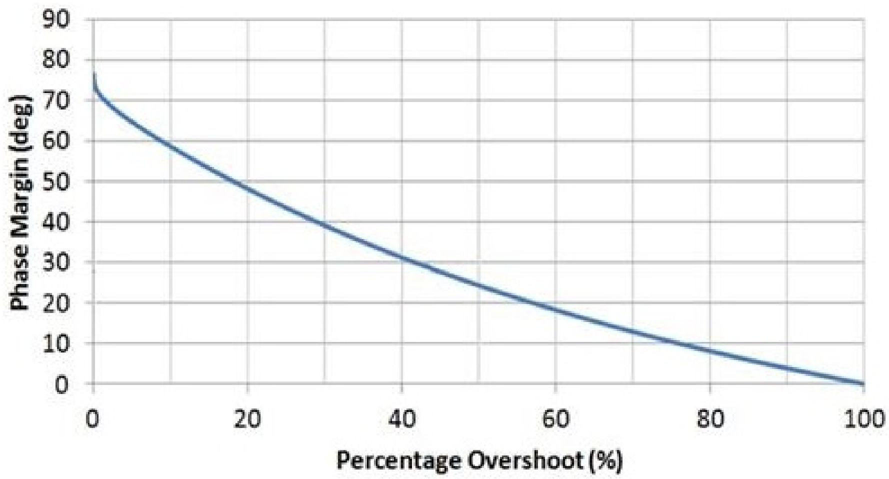


Figure 11. Phase Margin vs Percent Overshoot (Refer to TI Precision Labs Op Amps: Stability)

6.3 Open Load Testing - Worst Case for Stability

For a Class-D amplifier in PFFB, the most unstable condition is when the amplifier output is unloaded. Without a load, the Q (quality factor) of the LC filter will be extremely large. This causes extreme amplitude peaking at a frequency determined by the component values of the inductor (L) and capacitor (C).

Furthermore, the higher the Q, the quicker phase will shift –180° for incremental increase in frequency. This means the amplitude of the filter will still be very large when large phase shifts occurs. This causes instability.

Although a system is ideally stable with any phase margin greater than 0°, it is often desirable to design for a phase margin of 45° or greater to accommodate for mild phase shift from a reactive load.

If the amplifier is proven to have a stable open load, then the likelihood of stability issues when the amplifier output is loaded are reduced.

6.4 TPA3251 PFFB EVM Stability

To assess the stability of the TPA3251 in PFFB, the phase margin was calculated from the percent overshoot under various loading conditions using the standard PFFB configuration found in Section 1. PVDD = 36 V, Fpwm = 600 kHz.

6.4.1 TPA3251 PFFB Open Load

The scope images in Figure 12 have an overshoot of 66%, and a phase margin of 15°.

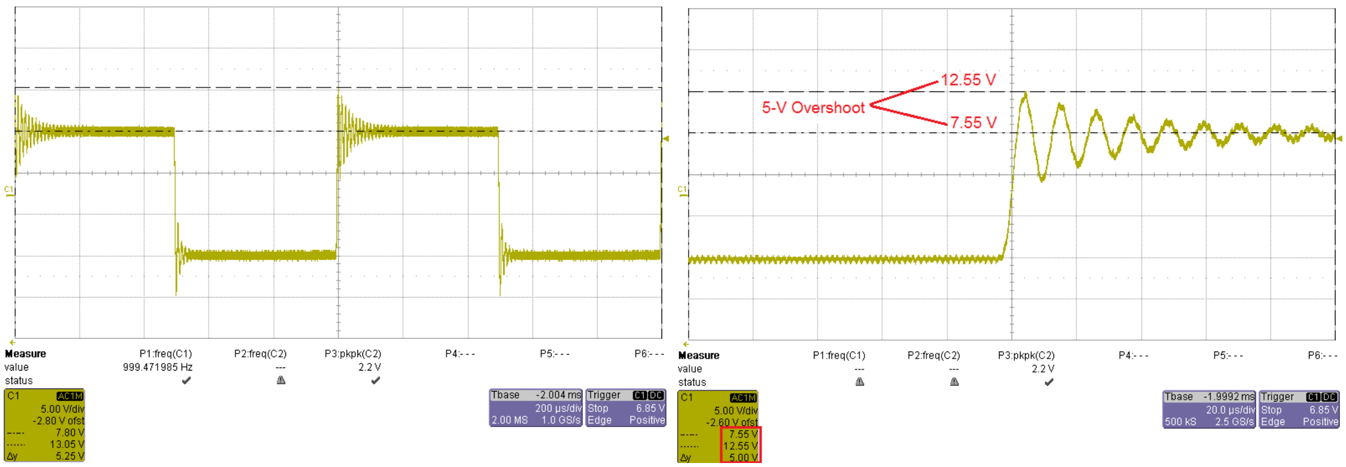


Figure 12. TPA3251 PFFB Overshoot Unloaded

6.4.2 TPA3251 PFFB 8-Ω Load

The scope images in Figure 13 have an overshoot of 21%, and a phase margin of 47°.

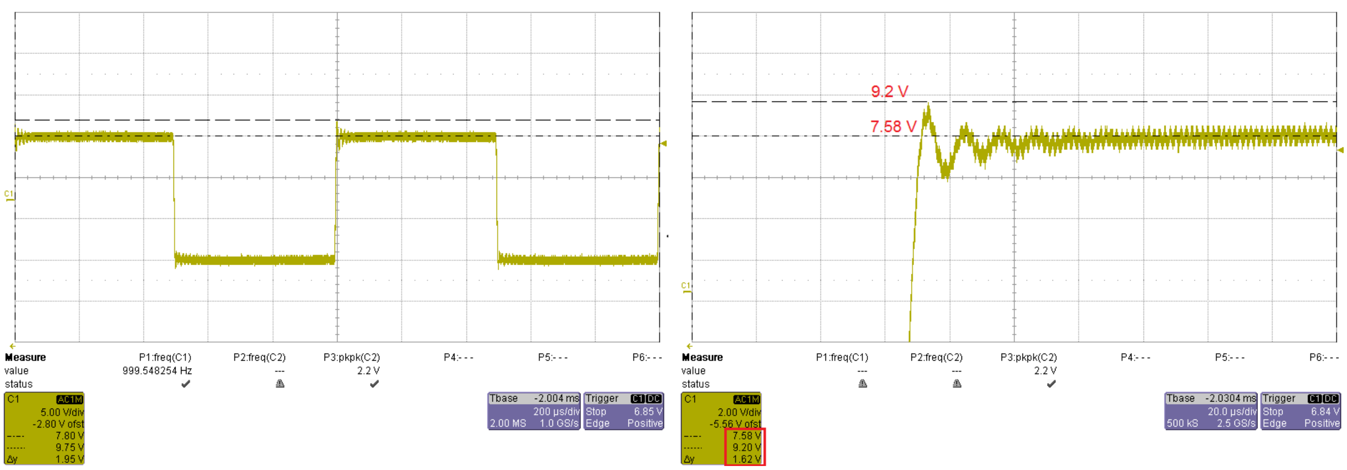


Figure 13. TPA3251 PFFB Overshoot 8-Ω Load

6.4.3 TPA3251 PFFB 4-Ω Load

The scope images in Figure 14 have an overshoot of 7%, and a phase margin of 64°.

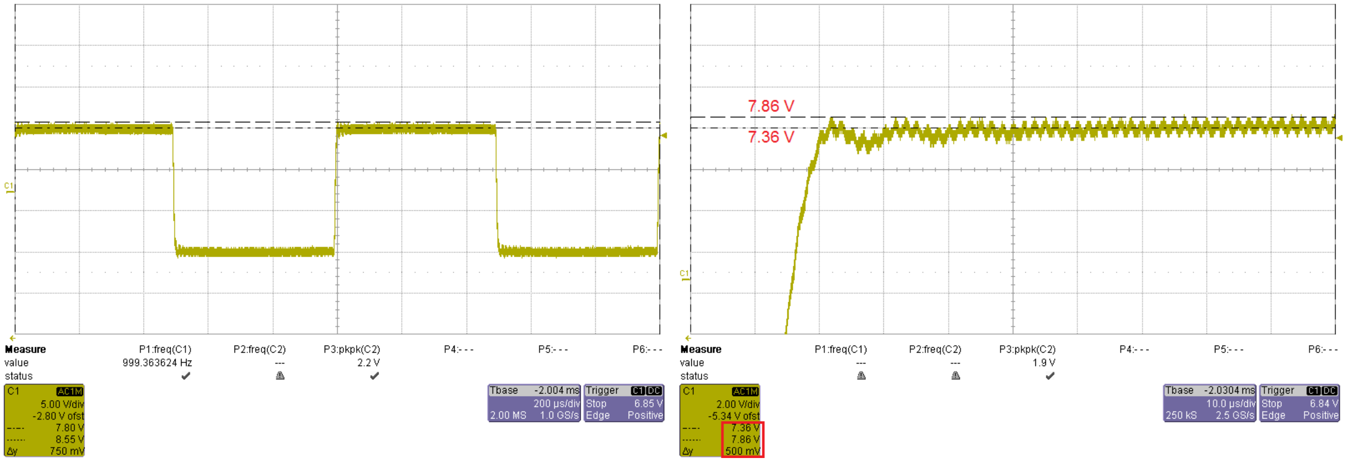


Figure 14. TPA3251 PFFB Overshoot 4-Ω Load

6.5 TPA3255 PFFB EVM Stability

To assess the stability of the TPA3255 in PFFB, the phase margin was calculated from the percent overshoot under various loading conditions using the standard PFFB configuration found in Section 1. PVDD = 51 V, Fpwm = 450 kHz.

6.5.1 TPA3255 PFFB Open Load

The scope images in Figure 15 have an overshoot of 97%, and a phase margin of 3°.

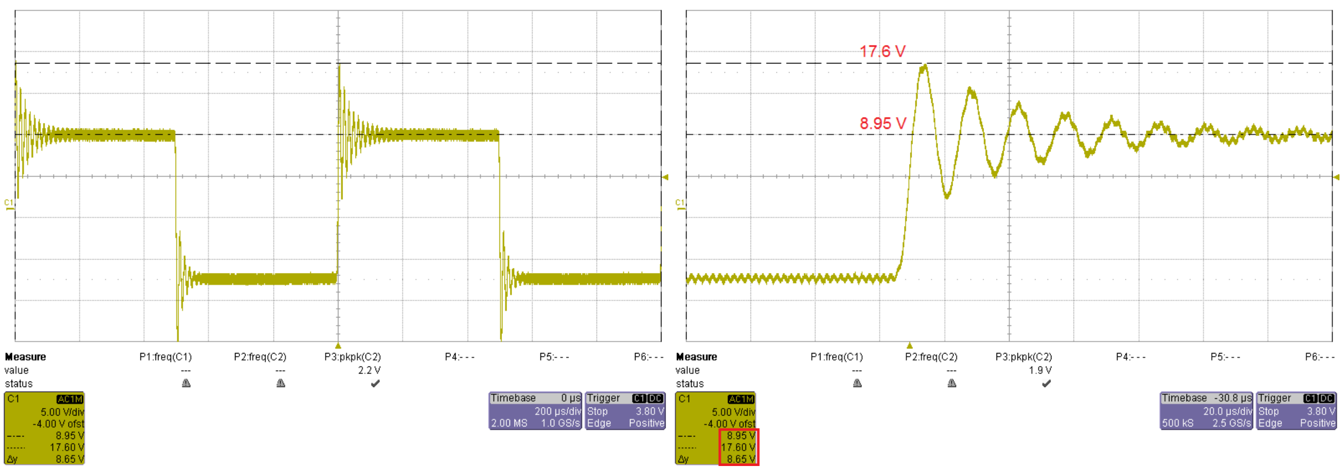


Figure 15. TPA3255 PFFB Overshoot Unloaded

6.5.2 TPA3255 PFFB 8-Ω Load

The scope images in Figure 16 have an overshoot of 39%, and a phase margin of 32°.

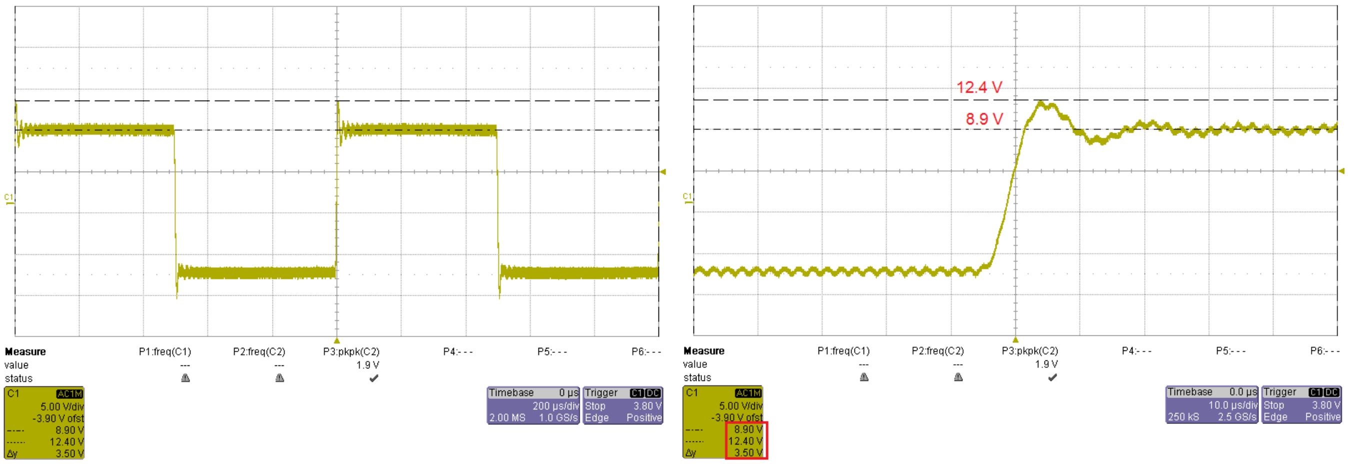


Figure 16. TPA3255 PFFB Overshoot 8-Ω Load

6.5.3 TPA3255 PFFB 4-Ω Load

The scope images in Figure 17 have an overshoot of 19%, and a phase margin of 49°.

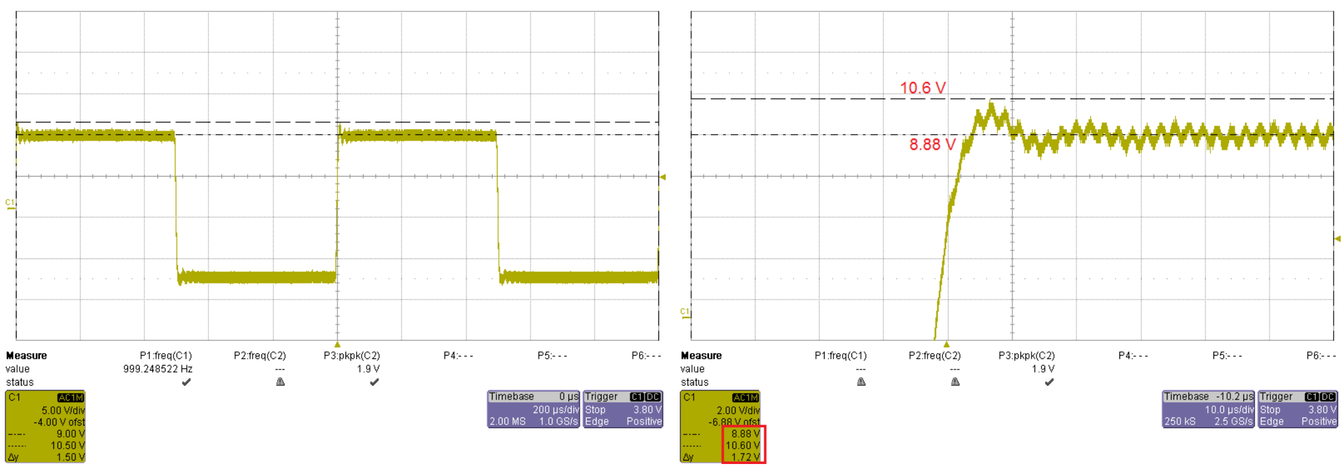


Figure 17. TPA3255 PFFB Overshoot 4-Ω Load

7 Further Reading

TI Precision Labs Op Amps: Stability 1: http://www.ti.com/lsds/ti/amplifiers-linear/precision-amplifier-precision-labs.page?DCMP=tipl&HQS=hpa-pa-opamp-tipl-bti-tr-en

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265