Application Report **Current and Voltage Sensing Accuracy and Linearity**

TEXAS INSTRUMENTS

ABSTRACT

Current and Voltage sense (IV sense) tracking is critical to the speaker protection algorithm in a smart audio amplifier. When IV Sense data is both accurate and responds linearly, then the speaker load resistance calculation will improve and allow the most power to be delivered into the speaker without damaging it. The speaker protection algorithm relies on this accurate sensing of current and voltage.

In order to characterize the electrical performance and ensuing accurate speaker protection algorithm can be built around the device, it is necessary to measure IV sense accuracy reliably and precisely. This article focuses on how to measure IVsense accuracy and linearity/gain error of pilot tone across audio signal power level and audio signal frequency using industry accepted instruments.

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Trademarks

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1



1 Equipment Setup

Typically bench measurements are performed using Audio Precision Analyzers. In the case of the AP2700 family of analyzers, there will be a Programmable Serial Interface Adapter (PSIA) which is used to drive and receive I²S data. When monitoring the Class-D outputs of audio amplifiers, it is also necessary to use a filter to assist the analyzer by resolving the output switching waveform.

When selecting a load, it is critical to use a resistor capable of easily handling the full-scale output voltage of the amplifier. Any changes in nominal resistance due to heating will reduce measurement accuracy. Additionally, wires used to connect the load need to be selected to minimize resistive losses at high output power.

Please refer to Figure 1-1 for a typical hardware setup:



Figure 1-1. Typical Hardware Setup

After connecting the AP analyzer as shown above, configure the analyzer software to use the following settings:



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Ch A Input: HiRe:	s A/D @65	536 \	Ch B		Freque	ncy: .999	1999 kHz	~	·	Audio Signal Frequency												
AC Coupled V Coupling AC Coupled V Frequency 2 60.0014 Hz V									→ P	ilot Tone Free	quency											
21.08 uV ∨ …Level… <u>7.789 uV</u> ∨ Dual Amp Ratio: 32.000 dB ∨									→ R	atio which se	ets Pilot to	ne Amp	litude									
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Channel Data Assig	gnment					Cha	nnel Data	Struct	ure		Channel Data Assignment Channel Data Structure											
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Data Channel	0	1					MSB First	\checkmark			Data Channel 0 1 MSB First 🗹											
I2S Loop	-Back F	lise / Fal	I		Pad	r	Data		Pad		I2S Rise / Fall Pad Data Pad											
Transmit Data Cloc	* (•			0 bit	s	24 Line	ear	✓ 8 b	its	R	leceive Data Clo	ick 🤅	0		0	bit	5	24 Bits	-	~	8 bits
PreEmphasis: Of	if	~	1		Low	/ L	Justify		R Low	~	DeEmphasis: Off											
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Frame Clock (Fs)		0				48.000	0 kHz	= 4	8.0000 kHz		F	rame Clock (Fs)						48.000) kHz	= 4	8.0000	kHz
Channel Clock	ОШТ	0				× 2	 channel	s = 9	6.0000 kHz	-1		Word Llock) Channel Clock	011					× 2	channel	s = 9	6 0000	kHz
(Subframe Clock)] bits/		07200 MU-	_		Subframe Clock) Dit Clock	0.0	0.0] bits/	- 0	07200	
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N*Fs	OUT					256	x Fs	= 1	2.2880 MHz	2	N	l¥Fs	OUT					256	x Fs	= 1	2.2880	MHz
Master Clock	Tx Out,	Bxln ∿	-				x Fs	= 1	2.2880 MHz		N	Master Clock	Tx Out,	Rxln ∨				256	x Fs	= 1	2.2880	MHz
-	Logic Voltage Level																					
	1		5		3.3 V	3.3 V	2.4 V	1.8	V						5 V	3	.3V	3.3 V	2.4 V	1.8	V	
Outputs	1											Outputs										
			0	TTL			CMOS	0	4							TTL		U	CMOS	0	1	

Figure 1-2. AP2700 Series Configuration

Once the analyzer is setup, configure the amplifier to generate IV sense data. This requires you to enable IV sense and then configure the I²S outputs to transmit both Isense and Vsense data. This can be easily done using the Pure Path Console 3 software associated with the EVM.

✓	Enable V-Sense	✓	Enable I-Sense
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Figure 1-3. Enable IV Sense Functions - Pure Path Console 3



Channel 1	
	Slot
I-Sense Transmit	0, 1
V-Sense Transmit	4, 5
VBAT Transmit	<u>~</u> +

Figure 1-4. Transmit IV Sense Data - Pure Path Console 3



2 Perform Measurements

It is critical to the reliability of this test that the load resistance be a known calibrated value. It is best to measure this using a 4-wire connection for the most accurate value. Several calculations will depend on the accuracy of this value.

The test will proceed in a stepwise manner across output power. At each power level of concern, the following data should be recorded:

 V_R = Voltage across the Resistor Only (CH B) V_L = Voltage across the (1) complete R+L Load (CH A) V_{dig} = Voltage Sense Digital Value (CH B) I_{dig} = Current Sense Digital Value (CH A)R = Calibrated Resistance

Measuring both Voltages and Digital inputs require changing the AP Input source between the HiRes A/D Converter and the Digital inputs.



Perform Measurements

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🚺 Digital Analyzer 📃 🔳 💌	🚺 Digital Generator 🛛 🗖 🖾											
Analyzer: DSP audio analyzer (analyzer) 🛛 🗸 🗸	Wfm: Sine V Dual V											
Ch A Input: HiRes A/D @65536 V Ch B	Frequency: .999999 kHz 🗸 🗸	Audio Signal Frequency										
AC Coupled V - Coupling - AC Coupled V	Frequency 2: 60.0014 Hz	> Pilot Tone Frequency										
21.08 uV 🗸 - Level 7.789 uV 🗸	Dual Amp Ratio: -32.000 dB 🗸	Ratio which sets Pilot tone Amplitude										
951941 kHz 🗸 Freq 8.47105 kHz 🗸	Auto On Track A	relative to Primary tone amplitude										
Range 🖉	Invert CHA Outputs OB CHB Invert											
19.28 uV 🗸 - Reading - 104.5 nV 🗸	-8.000 dBFS V - Amplitude - V	→Measure V _R here										
Measurement Furption : Bandpass 🗸 🗸	EQ Curve											
Range 🗹	V Post EU -											
Det: Auto V RMS V BP/BR Filtr Freq	Dither Type: Triangular 🗸											
BW: 22 Hz V 20kHz LP V Fixed V	Beterences	Bandpass fixed at Pilot										
Filt: Narrow V 60.0000 Hz V	Volts/FS: 1.000 V	tone Frequency										
der 1, 100.0 mEES V From 1,00000 kHz V	Freg: .997000 kHz											
dBr 2 100.0 mFFS ~ V/FS 1.000 V ~	dBr: 387.3 mFFS 🗸											
		The DELA Social Industries Description										
PSIA Serial Interface Transmitter		PSIA Senal Interface Receiver										
Channel Data Assignment	Channel Data Structure	Channel Data Assignment	Channel Data Structure									
Generator Channel A B	0 31	Analyzer Channel A B 0 31										
Data Channel U 1	MSB First 🗹	Data Channel U 1	MSB First 🗹									
I2S Loop-Back Rise / Fall	Pad Data Pad	I2S Rise / Fall Pad	Data Pad									
Transmit Data Clock 🛛 🔘 💿	0 bits 24 Linear ~ 8 bits	Receive Data Clock	24 Bits V 8 bits									
PreEmphasis: Off	Low V L Justify R Low V	DeEmphasis: Off	L Justify R									
Scale Freq. By: Output Rate (SR) ~		Scale Freq. By: Meas Input Rate V A: DESERTION AND A CONTRACT OF A CONTR										
Rate Ref: 48.0000 kHz		Rate Ref: 48.0000 kHz B: BABB	nananananananan Active Bits 🔿 Data Bits									
Bit Clock	Shift Bit	Bit Clock Shift Bit										
Clocks Direction Edge Sync Inver Out / In Rise / Fall W/m	t 1 bit Wide Computed left Pulse Setting Rate	Clocks Direction Edge Sync Invert 1 bit Wide Out / In Rise / Fall Wfm left Pulse	Computed Setting Rate									
Frame Clock (Fs)	Image: Weight of the second region 48.0000 kHz = 48.0000 kHz	Frame Clock (Fs)	48.0000 kHz = 48.0000 kHz									
Channel Clock (Subframe Clock) OUT O	x 2 channels = 96.0000 kHz	Channel Clock [Subframe Clock] OUT O C .	2 channels = 96.0000 kHz									
Bit Clock	x 32 bits/ = 3.07200 MHz	Bit Clock O	32 bits/ = 3.07200 MHz									
N*Fs OUT	256 x Fs = 12.2880 MHz	N*Fs OUT	256 x Fs = 12.2880 MHz									
Master Clock Tx Out, Rx In ~	x Fs = 12.2880 MHz	Master Clock Tx Out, Rx In V	256 x Fs = 12.2880 MHz									
	Voltage Level											
5V	3.3V 3.3V 2.4V 1.8V	5V 3.3V	3.3V 2.4V 1.8V									
Outputs		Outputs 🚥 🔳										
0		0 0										
	TTL CMOS	TTL TTL	CMOS									

Figure 2-1. Measuring Analog Voltages - Use HiRes A/D



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Analyzer: DSP audio analyzer (analyzer) V Wfm: Sine V Dual V																	
Ch A Input: Digital @ ISR V Ch B Frequency: 999999 kHz V								Audio Signal Frequency									
AC Coupled V Coupling AC Coupled V Frequency 2: 60.0014 Hz V								Pilot Tone Frequency									
FFSFFS								Ratio which sets Pilot tone Amplitude									
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Range 🗸	~	Inve	rt CHA	Outputs 🐽	СНВ	Invert											
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dBr 2: 100.0 mFFS ♥ V/FS: 1.000 V			UB1. 001	.5 11115	×												
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Data Channel 0 1				MSB First			Data Channel 0 1 MSB First 🗹										
125 Loop-Back		Pa	d	Data		Pad	12S Pad Data Pad										
Transmit Data Clash		0	bits	24 Linea	ər v	8 bits	Hise / Fall 0 bits 24 Bits v 8 bits										
		Low	~ L	Justify	B	Low ~		Neceive Data Cluc	K IG					L	Justify	R	
PreEmphasis: Off ~		Lannan					DeEmphasis: Off 24 20 16 12 8 4										
Scale Freq. By: Output Rate (SR) V							Scale Freq. By: Meas Input Rate V A: COMMANDER COMMANDER BY AN AND A COMMANDER BY A COMMANDER CO										
Hate Het: 48.0000 KHz							Hate Het: 48.0000 kHz O Active Bits O Data Bits										
Bit Clock		Shift E	Bit							Bit Clock		Shift	Bit				
Clocks Direction Edge Sync	Invert	1 bit W	'ide dee Cation			Computed Bate		Clocks	Direction	Edge Sync Bise / Fall	Invert	1 bit	Wide	Calling		Cor	mputed Bate
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(Word Clock)				channels		000 242		(Word Clock) Channel Clock	0.00				_		annels -	- 96.000	
(Subframe Clock) 001 0 0		L		bits/	- 30.0			(Subframe Clock)		• •	-					30.0000	
Bit Clock O			x 32	channel	= 3.07	'200 MHz		Bit Clock	0 •					x 32 ch	iannel	3.07200) MHz
N*Fs OUT			256	x Fs	= 12.2	2880 MHz		N*Fs	OUT					256 x F	s =	12.2880) MHz
Master Clock Tx Out, Rx In 🗸				x Fs	= 12.2	2880 MHz		Master Clock	Tx Out, I	Rxln ∽				256 x F	-s =	12.2880) MHz
	.ogic Vo 5 V	жаде Le 33∿	vei / 33V	24V	1.8V						Logic V 5 V	utage 3	Level 3 V	33V 2	4V	1.8V	
Outputs								Outputs @									
	0	0		0	0						0	(C		C	0	
1	T	TTL		CMOS								TTL		CM	IOS		

Figure 2-2. Measuring Digital Outputs - Use Digital Interface

Proceed to capture each of the above values, step the output power to the next amplitude, and repeat until the full output range under test is captured. However, in this configuration, the pilot tone amplitude is a scalar ratio of the fundamental. You only want to increase the magnitude of the fundamental, so this ratio will require adjustment at each step. Setting the ratio and the amplitude in units of dB will allow for easy adjustments. As long as the sum of the ratio and amplitude is kept constant, the pilot tone amplitude should remain fixed.

Once data collection is complete, you can perform calculations for each output level to determine accuracy.

7



$$V_{FS} = Full Scale Voltagel_{FS} = Full Scale Currentl_{actual} = \frac{V_R}{R}V_S = (2)$$

$$\frac{V_{dig} * V_{FS}}{2}I_S = \frac{I_{dig} * I_{FS}}{2}V_{accuracy}(\%) = \frac{(V_S - V_L) * 100}{V_L}I_{accuracy}(\%) = \frac{(\frac{V_S - V_L}{V_L}) * 100}{V_L}I_{accuracy}(\%) = \frac{(\frac{V_S - V_L}{I_{actual}}) * 100}{\frac{V_L}{I_{actual}}}$$

It is necessary to determine the full scale voltage and current values from the data sheet of the amplifier being used. For example, you can pull this information for TAS2562 in Figure 2-3:

	,		1	
CURRENT SENSE				
DNR	Dynamic range	Un-Weighted, Relative to 0 dBFS	69	dB
	Total harmonia distartian + poiss	$\rm R_L$ = 8 Ω + 33 µH, f _{in} = 1 kHz, P _{OUT} = 1 W	-56	dB
	Total harmonic distortion + hoise	R_L = 4 Ω + 33 μ H, f _{in} = 1 kHz, P _{OUT} = 1 W	-57	dB
	Full-scale input current		2.0	Α
	Current-sense accuracy	R_L = 8 Ω + 33 µH, I _{OUT} = 354 mA _{RMS} (P _{OUT} = 1 W @ 1kHz)	±1	%
	Current-sense gain error over temperature	0°C to 70°C, 8 Ω, using a 60Hz -40dB pilot tone	±1	%
	Current-sense gain error over output power	50mW to 0.1 % THD+N level, f_{in} = 1 kHz, 8 $\Omega,$ using a 60Hz -40dB pilot tone	±1.5	%
		fs = 8 kHz to 48 kHz	0.417	fs
	LPF passband corner	fs = 96 kHz	0.208	fs
		fs = 192 kHz	0.104	fs
	LPF passband ripple		-0.05 0.05	dB
	LPF stopband attenuation	0.55 fs	60	dB
	LPF group delay	DC to 0.417 fs	5.7	1/fs
VOLTAGE SENSE				
DNR	Dynamic range	Un-Weighted, Relative 0 dBFS	69	dB
THE	Total harmonic distortion 4 pairs	$\rm R_L$ = 8 Ω + 33 $\mu \rm H,~f_{in}$ = 1 kHz, $\rm P_{OUT}$ = 1W	-60	dB
THD+N	Total harmonic distortion + hoise	R_L = 4 Ω + 33 μH, f _{in} = 1 kHz, P _{OUT} = 1W	-60	dB
	Full-scale input voltage		14	V _{PK}
	Voltage-sense accuracy	$ \begin{array}{l} R_{L} = 8 \; \Omega + 33 \; \mu H, \; I_{OUT} = 354 \\ m A_{RMS} \; (P_{OUT} = 1 \; W) \end{array} $	±0.5%	
	Voltage-sense gain error over temperature	0°C to 70°C, 8 Ω, using a 60Hz -40dB pilot tone	±0.5%	
			-	

Figure 2-3. TAS2562 Full Scale Values



3 Linearity Calculations

Linearity, or Gain Error, can be easily calculated for each accuracy measurement in *Section 2*. To do this, a reference value should be selected from the set of data. It is typical to use the condition of 1 W, 1 kHz, and 25°C. Linearity for each data point is then the difference from its respective reference value.

```
I_{linearity} = I_{accuracy} - I_{ref}V_{linearity} = V_{accuracy} - V_{ref}Load_{linearity} = Load_{accuracy} (3)
- Load_{ref}
```

These values can then be plotted to show the changes in accuracy relative to the reference for each calculation. Fixed offsets to this data can be calculated out easily, but it is most desirable to see this line be flat and centered at zero for the best speaker protection performance. Figure 3-1 sample plot.



Figure 3-1. Sample Plot



4 Summary

The test flow for evaluating IV Sense linearity and accuracy is a typical part of the design validation and characterization. It is helpful to know the overall expected accuracy. Many devices available from TI.com such as TAS2562, TAS2563, TAS2564, and TAS2770 are able to meet 1% accuracy or better across power and temperature. This allows the SmartAmp algorithm to provide superior speaker protection while maximizing output power into small speakers.



5 References

- TAS2562 Digital Input Mono Class-D Audio Amplifier with Speaker IV Sense Data Sheet
- TAS2563 6.1-W Boosted Class-D Audio Amplifier with Integrated DSP and IV Sense Data Sheet
- TAS2564 7-W Boosted Class-D Audio Amplifier with <10 μV Noise and IV Sense Data Sheet
- TAS2770 20-W Digital Input Mono Class-D Audio Amplifier with Speaker IV Sense Data Sheet

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